Metrology Measurement Capabilities

Federal Manufacturing & Technologies

Dr. Glen E. Gronniger

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Final Report

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Introduction

This document contains descriptions of Federal Manufacturing & Technologies (FM&T) Metrology capabilities, traceability flow charts, and the measurement uncertainty of each measurement capability.

Metrology provides NIST traceable precision measurements or equipment calibration for a wide variety of parameters, ranges, and state-of-the-art uncertainties. Metrology laboratories conform to the requirements of the Department of Energy Development and Production Manual Chapter 13.2, ANSI/ISO/IEC ANSI/ISO/IEC 17025:2005, and ANSI/NCSL Z540-1.

FM&T Metrology laboratories are accredited by NVLAP for the parameters, ranges, and uncertainties listed in the specific scope of accreditation under NVLAP Lab code 200108-0. See the Internet at http://ts.nist.gov/Standards/scopes/2001080.pdf. These parameters are summarized on the following page.

The Honeywell Federal Manufacturing & Technologies (FM&T) Metrology Department has developed measurement technology and calibration capability in four major fields of measurement:

- Mechanical
- Environmental, Gas, Liquid
- Electrical (DC, AC, RF/Microwave)
- Optical and Radiation

Metrology Engineering provides the expertise to develop measurement capabilities for virtually any type of measurement in the fields listed above.

A strong audit function has been developed to provide a means to evaluate the calibration programs of our suppliers and internal calibration organizations. Evaluation includes measurement audits and technical surveys.

Measurement and Calibration Capabilities
*NVLAP Accredited in these parameters

Dimensional
- Length *
- Coordinate Measuring Machines *
- Coordinate Measurement *
- Angle Measurement *
- Gage Blocks *
- Glass Scales *
- Internal/External Diameters *
- Roundness *
- Spherical Diameter *
- Flatness Measurement *
- Thread Wires *
- Surface Finish Measurement

Angle, Roughness, and Flatness
- Angle *
- Surface Roughness
- Optical Surface Flatness *
- Surface Plate Flatness *

Mass, Force and Torque
- Mass *
- Force *
- Torque

Vibration, Acceleration, Shock, Sound Level
- Vibration *
- Shock *
- Sound Level

Environmental, Gas, Liquid
- Temperature *
- Fixed Point Temperature *
- Humidity
- Pressure *
- Gas Flow
- Leak Rate *
- Air Velocity*

Electrical AC/DC
- AC/DC Voltage *
- AC/DC Current
- AC/DC Resistance *
- Capacitance, Inductance *
- Frequency, Time *
- DC Magnetic Field Density

Electrical RF/Microwave
- Attenuation *
- RF Power *
- RF Reflection Coefficient *
- Network Analyzers

Specific Gravity, Laboratory Glassware Volume
- Specific Gravity
- Laboratory Glassware Volume
  - Burets
  - Volumetric Pipets
  - Measuring Pipets
  - Volumetric Flasks
  - Graduated Cylinders

Optical Radiometric, Photometric
- Optical Transmittance
- Optical Spectral Response
- Laser Average Power
- Laser Peak Power
- LED Power
- Ultraviolet Irradiance
- Illuminance
- Monochrometers
- X-Ray Film Density
- Luminous Intensity
- HeNe Laser Frequency, Wavelength *

Mechanical

Dimensional

Length and Coordinate Measurement

General length and coordinate standard measurements are made on a custom built coordinate measuring machine (CMM). The CMM is a fixed bride, all-granite machine using air bearings for all guide ways. The CMM uses laser interferometers to measure displacement. The probing system is an active analog scanning type probe. The CMM has also been fitted with a video microscope system to perform measurements of glass grid plates and line scales. Uncertainties are listed in the accompanying tables.

Shelton CMM with CMM Calibration Artifact

Gage Block Measurement

Gage blocks are compared to blocks certified by the Primary Standards Laboratory (PSL) using a gage block comparator.

Roundness Measurement

Roundness measurements are made using a roundness machine with an air-bearing spindle. Spindle error measurements are made using a reversal technique that separates spindle error from roundness error.

Gage Block Calibration

Flatness Measurement

Flatness of small surfaces is measured directly using an optical flat or an optical interferometer. Reference optical flats are calibrated using the three-flat method and a polychromatic fringe viewer. Surface plate flatness is measured using an autocollimator and mirror(s). The flatness of the surface plate is determined using both the Moody method and a three-dimensional least squares technique.

Dimensional Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) k=2***
Gage Blocks	To 4 in.	2.6 μin. + 0.3 ppm
	> 4 to 20 in.	6.7 μin. + 0.3 ppm
Coordinate Measurement *	Axial	10 μin + 0.3 ppm
	Planar **	30 μin. + 0.5 ppm
1-D Ball Plates	To 48 in.	20 μin + 0.7 ppm.
2-D Ball Plates	36 in. by 36 in.	20 μin + 0.7 ppm.
Step Gages	To 24 in.	15 μin + 0.6 ppm.
Internal Diameters	0.04 to 1 in. 1 to 14 in.	10 μin Determined by Test
Single Axis Glass Line Scales	0 to 16 in.	15 μin + 0.5 ppm.

Dimensional Measurement Capability

Type	*Range*	*Measuring Uncertainty (±) k=2*
Spherical Diameter	0 to 1 in. 1 to 2 in.	8.3 µin. 16 µin.
Cylindrical Plug Gages	0 to 1 in.	6.2 µin.
Squares	To 24 in. by 36 in.	30 µin.
Straight Edges	To 48 in.	5 µin.
Roundness	To 18-in. diameter	2 µin.
Thread Wires	All standard pitches	8 µin.

* Maximum range of length-coordinate measurement is x = 48 in., y = 36 in., and z = 12 in.

** Certain artifacts, such as ball plates, can be designed in such a way to allow the use of a single-axis calibration technique. The technique requires the balls to be located in an orderly array with one ball located in the center. Artifacts of this design can be certified to ±(20 µin + 0.7 ppm).

Angle Measurement

Small angles are measured using an autocollimator. The autocollimator is calibrated using a small-angle generator consisting of a pivot arm of known length and a set of certified gage blocks. Large angles are measured using an autocollimator, a rotary table, an optical polygon, and angle gage blocks.

Surface Finish Measurement

Surface finish standards are measured using a profile-type surface finish analyzer. The surface finish analyzer is calibrated using a lever arm calibrator and roughness standards calibrated by NIST.

Dimensional Standards

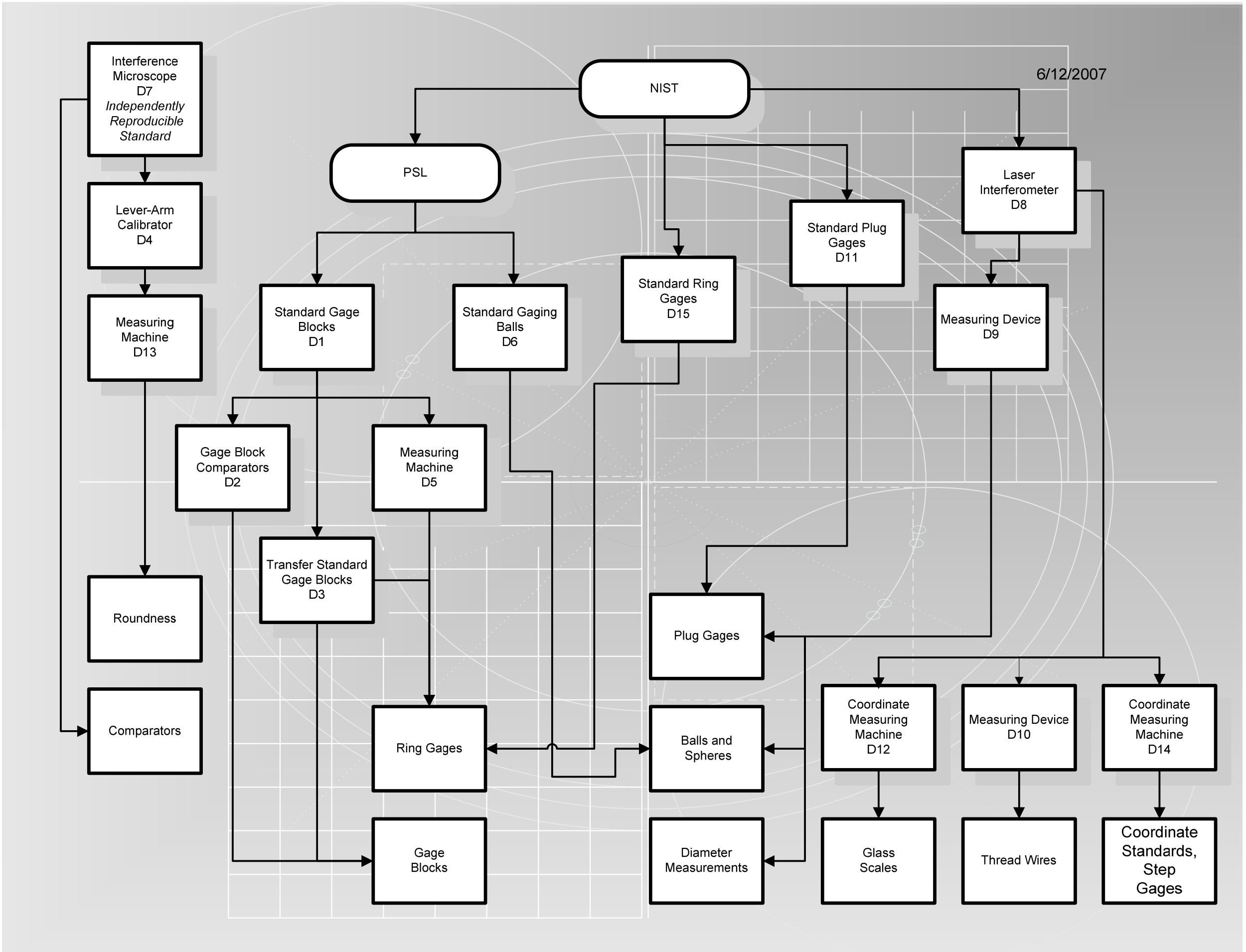
Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
D1	Standard Gage Blocks	Do All Pratt & Whitney	To 4 in. 5 to 20 in.	1.53 µin. + 0.7 ppm 0.7 µin. + 5.7 ppm
D2	Gage Block Comparators	Link Federal Federal	0 to 2 in. 0 to 4 in. 5 to 20 in.	3 µin. 3 µin. 3 µin.
D3	Transfer Standard Gage Blocks	Do All Pratt & Whitney	To 4 in. 5 to 20 in.	2.6 µin. + 0.3 ppm 6.7 µin. + 0.3 ppm

Dimensional Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
D4	Lever Arm Calibrator	FM&T Metrology	0 to 0.0002 in.	0.25 µin. + 0.5% of travel
D5	Measuring Machine	Pratt & Whitney	0 to 14 in.	3 µin. + 2 ppm
D6	Standard Gauging Balls	AA Industries	1/16 to 1 in.	6 µin.
D7	Interference Microscope	Zeiss	0 to 0.01 in.	1 µin.
D8	Laser Interferometer	Hewlett-Packard	N/A	0.05 ppm
D9	Measuring Machine	Pratt & Whitney	1 in.	10 µin.
D10	Measuring Machine	FM&T Metrology	0 to 2 in.	8 µin.
D11	Standard Plug Gages	Lincoln	0.050 to 1 in.	4.6 µin.
D12	Coordinate Measuring Machine	SIP/FM&T Metrology	0 to 16 in	Included in Line Scale Process
D13	Roundness Measuring Machine	Bendix A & M	18-in. diameter	2 µin.
D14 *	Coordinate Measuring Machine	Shelton	Axial	10 µin. + 0.3 ppm
			x-y plane**	30 µin. + 0.5 ppm
D15	Standard Ring Gages	FM&T Metrology	0 to 1 in.	4.6 µin.

* Maximum range: x = 48 in., y = 36 in., z = 12 in.

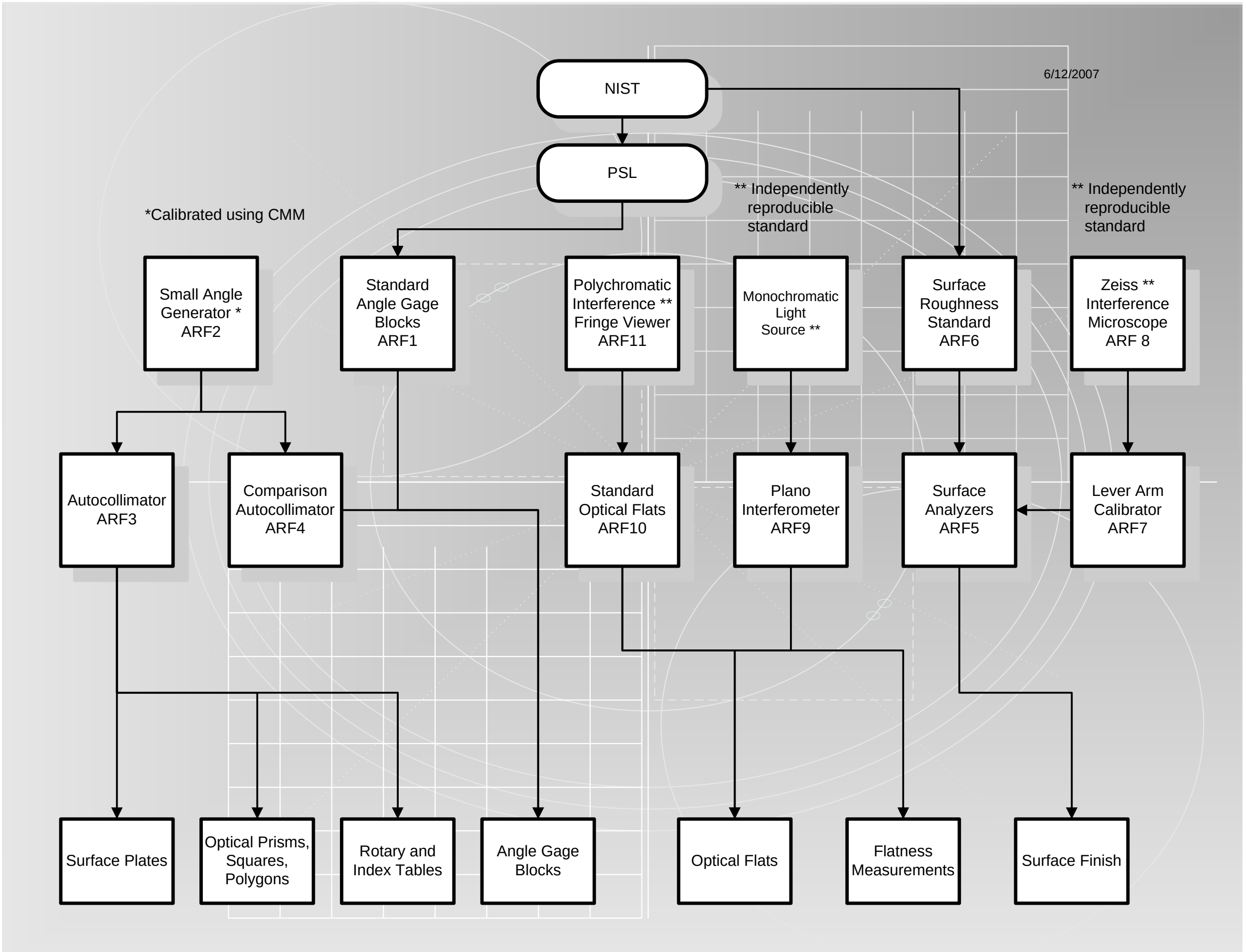
** Certain artifacts, such as ball plates, can be designed in such a way to allow the use of a single-axis calibration technique. This requires the balls to be located in an orderly array with one ball located in the center. Artifacts of this design can be certified to ±(20 µin + 0.7 ppm.).



Dimensional Calibration Traceability

Angle, Roughness, and Flatness Measurement Capability

Type	Range	Measuring Uncertainty (±) (k=2)
Angle (Polygon/Index Table)	0 to 360°	0.4 arc second
Angle Blocks	To 45°	1.1 arc second
Autocollimators	0 to 30 arc seconds 0 to 600 arc seconds	0.10 arc second 0.2 arc second + 0.2%
Surface Roughness	0.024 in. (Peak-to-Peak)	0.4 + 1.2% of Reading (in µin. Ra)
Optical Surface Flatness	To 12-in. diameter	1.2 µin. (Three Flat Method) 2 µin. (Interferometer) 4 µin. (Direct Comparison)
Surface Plate Flatness	Up to 8 ft Diagonal	30 µin. + 2 µin./ft^2



Angle, Roughness, Flatness Traceability

Angle, Roughness, and Flatness Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
ARF1	Standard Angle Gage Blocks	Webber	1 arc second to 45° (16 blocks)	0.7 arc second
ARF2	Small Angle Generator	Matrix	10 arc minutes	0.05 arc second
ARF3	Autocollimator	Moeller-Wedel	20 arc minutes	0.10 arc sec
		Nikon	20 arc minutes	0.2 arc second + 0.2% of measured angle
ARF4	Comparison Autocollimator	Davidson	120 arc seconds	0.3 arc second + 0.5% of measured angle
ARF5	Surface Analyzer	Federal/Metrex	0.024 in. (peak to peak)	(0.4+1.2% of reading) μin. R_a
ARF6	Surface Roughness Standard	NIST	120 μin. R_a 39.5 μin. R_a 12.7 μin. R_a	1.77 μin. R_a 0.59 μin. R_a 0.31 μin. R_a
ARF7	Lever-Arm Calibrator	FM&T Metrology	0 to 0.0002 in.	0.25 μin. +0.5% of travel
ARF8	Interference Microscope	Zeiss	0 to 0.01 in.	1 μin.
ARF9	Plano Interferometer	Davidson	2 3/4-in. diameter	2 μin.
ARF10	Standard Optical Flats (set of 3)	Do All	12-in. diameter	Flat within 4 μin.
ARF11	Polychromatic Interference Fringe Viewer	Strang	NA	1 μin.

Mass, Force, and Torque and Volumetric

Mass Measurement

Mass measurements are made by comparison to master weights or by direct weighing using ten precision balances. The 1kg master weights are calibrated by NIST and their measured value is disseminated to the rest of the master weights. Metrology also has the capability to perform extremely precise weighing on 1-2-3-5 or 1-2-2-5 decade progressions over the range of 1 mg to 50 kg.

Precision Balances

Force Measurement

Force transducers up to 2400-lbf capacity are measured using weight sets or dead weight testers, which are certified in force units in our Mass lab. Larger force devices are measured by comparison to NIST-calibrated proving rings using a universal force tester.

Small Load Cell Calibration

Dead Weight Force Calibration

Torque Measurement

Torque transducers are measured using weights, which are certified in force units in our Mass lab and lever arms of known length. The lever arms are calibrated on a coordinate measuring machine using a helium-neon laser as a standard.

Mass, Force, and Torque Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Mass (Direct Weighing)	1 mg to 20 g	0.01 to 0.11 mg
	> 20 to 200 g	0.19 to 0.7 mg
	> 200 to 2000 g	1.5 to 10 mg
	> 2000 to 10000 g	8 to 15 mg
	> 10000 to 50000 g	140 to 260 mg
	> 50000 to 60000 g	2 g
Mass (Direct Comparison)	1 mg to 5 g	0.0004 to 0.0015 mg
	10 to 100 g	0.026 to 0.033 mg
	200 to 1000 g	0.08 to 0.18 mg
	2000 g	0.6 mg
	3000 to 10000 g	1 to 27 mg
	20000 to 50000 g	57 to 103 mg
Mass (Double Substitution)	1 mg to 5 g	0.0003 to 0.0015 mg
	10 to 100 g	0.004 to 0.021 mg
	200 to 1000 g	0.08 to 0.18 mg
	2000 g	0.6 mg
	3000 to 10000 g	1 to 27 mg
	20000 to 50000 g	59 to 104 mg
Mass (Calibration Design Using 1-2-2/3-5 Decade Progressions)	1 mg to 5 g	0.0002 to 0.0026 mg
	10 to 100 g	0.005 to 0.047 mg
	200 to 1000 g	0.06 to 0.19 mg
	2000 to 5000 g	1 to 2 mg

Mass, Force, and Torque Measurement Capability

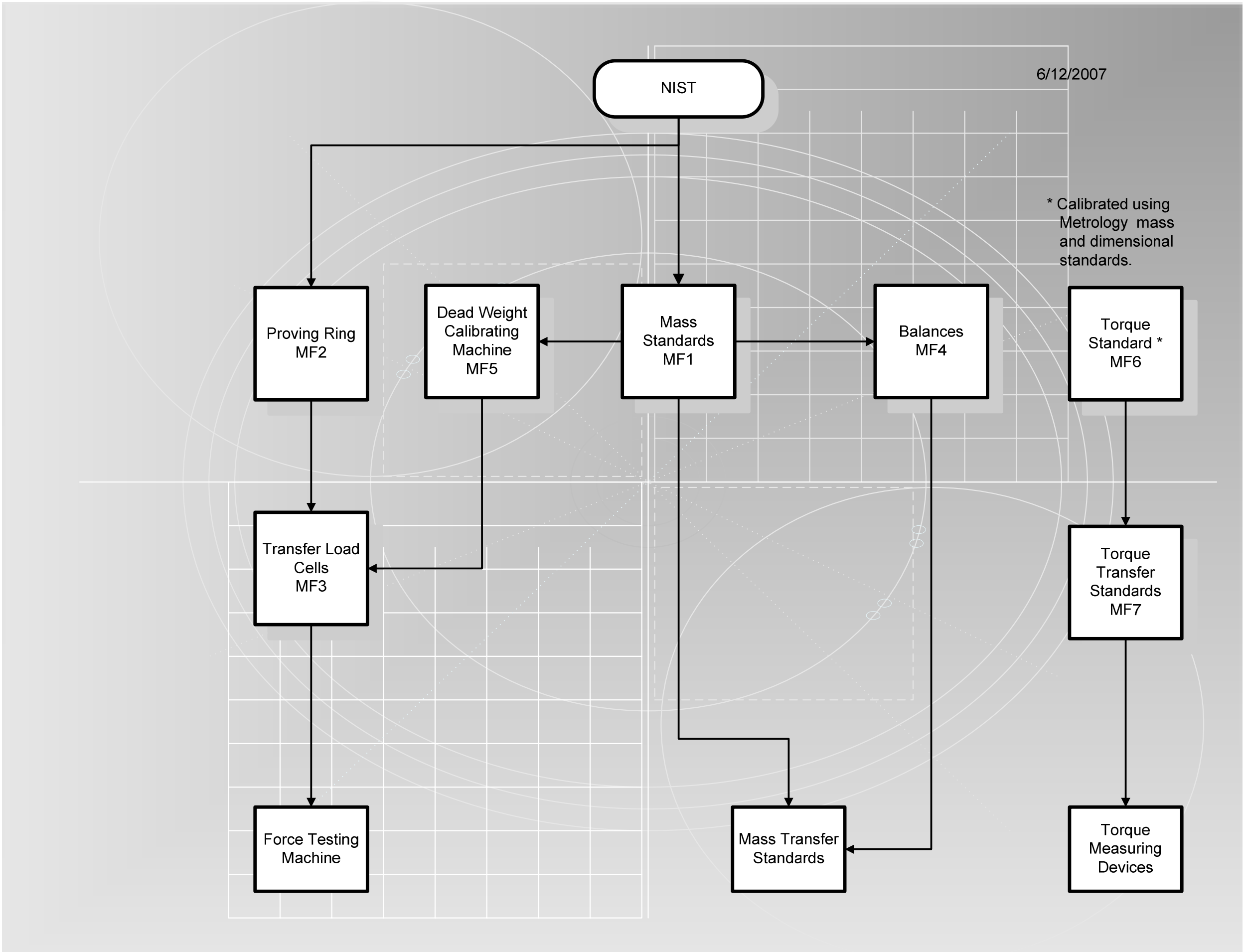
Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Force	0.0625 to 5 lbf	0.1% of reading
	5 to 500 lbf	0.005% of reading
	500 to 2400 lbf	0.005% of reading
	750 to 3000 lbf	0.45 lbf
	3000 to 5000 lbf	0.75 lbf
	5000 to 10000 lbf	2.0 lbf
	10000 to 30000 lbf	5.0 lbf
	30000 to 100000 lbf	15.0 lbf
Torque	1 ozf-in. to 700 lbf-ft	0.17% of reading

Laboratory Glassware Volume

Laboratory glassware volume is measured by the gravimetric method using precision balances and distilled water.

Laboratory Glassware Volumetric Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Laboratory Glassware Volume		
Burets	10 to 100 mL	NIST or ASTM Class A, B
Volumetric Pipets	0.5 to 100 mL	NIST or ASTM Class A, B
Measuring Pipets	1 to 30 mL	NIST or ASTM Class A, B
Volumetric Flasks	1 to 5000 mL	NIST Class A, B
	5 to 2000 mL	ASTM Class A, B
Graduated Cylinders	5 to 2000 mL	NIST or ASTM Class A, B



Mass, Force, and Torque Traceability

Mass, Force, and Torque Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
MF1	Mass Standards	Troemner, Rice Lake	1 mg to 100 g	0.000053 to 0.017 mg
		Troemner	200 g to 20000 g	0.027 to 85 mg
		Troemner	1 lb to 50 lb	2 ppm
MF2	Proving Rings	Morehouse	3000 to 100,000 lbf	0.015 to 0.02% of range
MF3	Transfer Load Cells	Various	0 to 240,000 lbf	0.05% F.S. + 0.1% load
MF4	Balances	Mettler Toledo	0 to 6.1 g	Comparison
	(uncertainties listed are for direct weighing)	Mettler Toledo	0 to 22 g	5 ppm + 0.01 mg
		Mettler Toledo	0 to 111 g	Comparison
		Mettler Toledo	0 to 205 g	3 ppm + 0.1 mg
		Mettler Toledo	0 to 1109 g	Comparison
		Mettler Toledo	0 to 2300 g	5 ppm
		Mettler Toledo	0 to 10100 g	1 ppm + 5 mg
		Mettler Toledo	0 to 52000 g	4 ppm + 60 mg
		Mettler	0 to 5000 g	3 ppm + 11 mg
		Mettler	0 to 60 kg	2 g
MF5	Dead Weight Calibrating Machine	Morehouse (modified)	5 to 500 lbf	0.005% of reading
	Dead Weight Calibrating Machine	FM&T Metrology	50 to 2400 lbf	0.005% of reading
MF6	Torque Standard	FM&T Metrology	0 to 700 lbf-ft	0.17% of reading
MF7	Transfer Torque Standard	Norbar	0 to 700 lbf-ft	0.2% of range + 0.5% of reading

Shock and Vibration

Vibration

Standard accelerometers are calibrated at NIST and certified for the transfer of its sensitivity to the Vibration Systems transfer standard accelerometer. The vibration system transfers the sensitivity to other accelerometers. Sensitivity can be determined at ambient temperature or over the range of –70 to +125°C. A control standard is measured on the vibration system to verify that the system is functioning properly.

Vibration Calibration System with Environmental Capability

Mechanical Shock

The shock standard accelerometer and accelerometers calibrated for shock levels above 10,000 g’s are calibrated using a velocity change shock pulse generator. The area of the shock pulse and the time of flight through a known distance are captured to calculate the sensitivity using the velocity change method. Accelerometers calibrated for shock less than 10,000 g’s are calibrated in a back-to-back configuration on a hammer-activated shock pulse generator by comparison to the shock standard accelerometer.

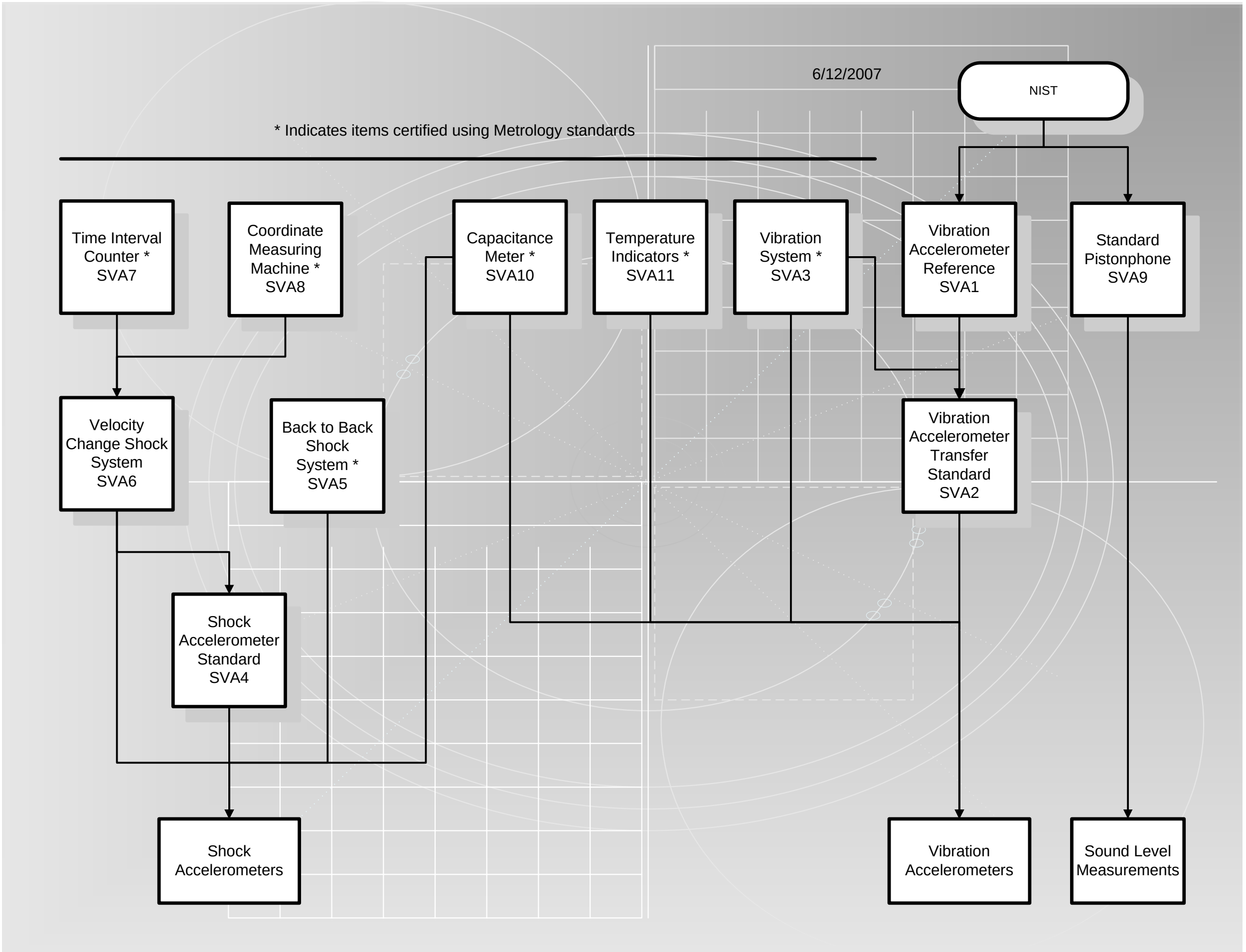
Velocity Change Shock Pulse Generator

Sound Level

Calibration of sound level is made by comparison of a sound level meter to a standard piston phone that is calibrated at NIST.

Vibration, Acceleration, Shock, Sound Level Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Vibration	10 g at 100 Hz to 10 kHz at -65 to +125°C	1.8 to 4.0%
Shock	2 to 15,000 g at 0.05 to 10 ms	2.5 to 3.0%
Sound Level	94 to 124 dB at 250 Hz	0.5 dB



Vibration, Shock, Sound Level Traceability

Vibration, Acceleration, and Shock Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
SVA1	Vibration Accelerometer Reference	Endevco	2 to 10 g 2 Hz to 10 kHz	1 to 2%
SVA2	Vibration Accelerometer Transfer Standard	Unholtz Dickie	2 to 10 g 2 Hz to 10 kHz	1.8 to 2.5%
SVA3	Vibration System	FM&T	2 to 20 g 2 Hz to 10 kHz	Used only with other calibrated measuring standards
SVA4	Shock Accelerometer Standard	Endevco	10 to 10,000 g	3%
SVA5	Back to Back Shock System	FM&T Metrology	100 to 10,000 g	Used only with other calibrated measuring standards
SVA6	Velocity Change Shock System	FM&T Metrology	500 to 15,000 g	2.5 to 3.0%
SVA7	Time Interval Counter	Hewlett Packard	10 μsec to 1 ms	0.05% of reading
SVA8	Coordinate Measuring Machine	Brown & Sharp	0 to 0.5 in.	±0.0003 in. from nominal
SVA9	Standard Piston phone	B and K	124 dB at 250 Hz	0.25 dB
SVA10	Capacitance Meter	Data Precision	to 1 μF	0.1% of reading + 1 digit
SVA11	Temperature Indicators	Keithley	-65°C to +125°C	1°C

Environmental, Gas, Liquid

Temperature

Temperature measurements in Metrology are based on the International Temperature Scale of 1990 (ITS-90). There are three primary standards at FM&T for temperature calibration: fixed point cells, the standard platinum resistance thermometer (SPRT), and the platinum / 10% rhodium versus platinum thermocouple (type S).

Automated Temperature Calibration

<u>SPRT Calibration Using a Fixed Point Temperature Cell</u>

The SPRT covers the range from -180 to 660°C and is certified to an accuracy of ±(0.006 to 0.05°C). The type S thermocouple covers the range from 0 to 1450°C and is certified to an accuracy of ±0.3°C from 0 to 1100°C increasing linearly to 1.6°C at 1450°C.

Temperature environments for calibrations are created with two stirred baths, two drywell furnaces, a horizontal tube furnace, and fixed point temperature cells. The first stirred bath contains Fluorinert and covers the range from -80 to +100°C . The second bath contains silicon oil and covers the range from 50 to 260°C. Both baths are used to calibrate thermocouples, SPRTs, thermistors, liquid-in-glass thermometers, and some solid state sensors. The drywells cover the range of -30 to 500°C and are used to calibrate thermocouples and industrial Platinum Resistance Thermometers. The horizontal tube furnace covers the range from 100 to 2700°F and is used to calibrate different types of thermocouples in air. Fixed-point temperature cells make possible very accurate single point temperature measurements for SPRTs and thermocouples.

These cells are (temperatures in ITS-90 scale) Mercury (-38.8344°C), Water (0.01°C), Gallium (29.7646°C), Indium (156.5985°C), Tin (231.928°C), Zinc (419.527°C), and Aluminum (660.323°C).

Humidity

Humidity calibrations are performed with two instruments. The first is a frost point generator capable of generating frost points from -75°C to 10°C ±0.5°C. The second is a two-pressure system that can generate humidity from 5% to 95% RH to ±0.5% RH.

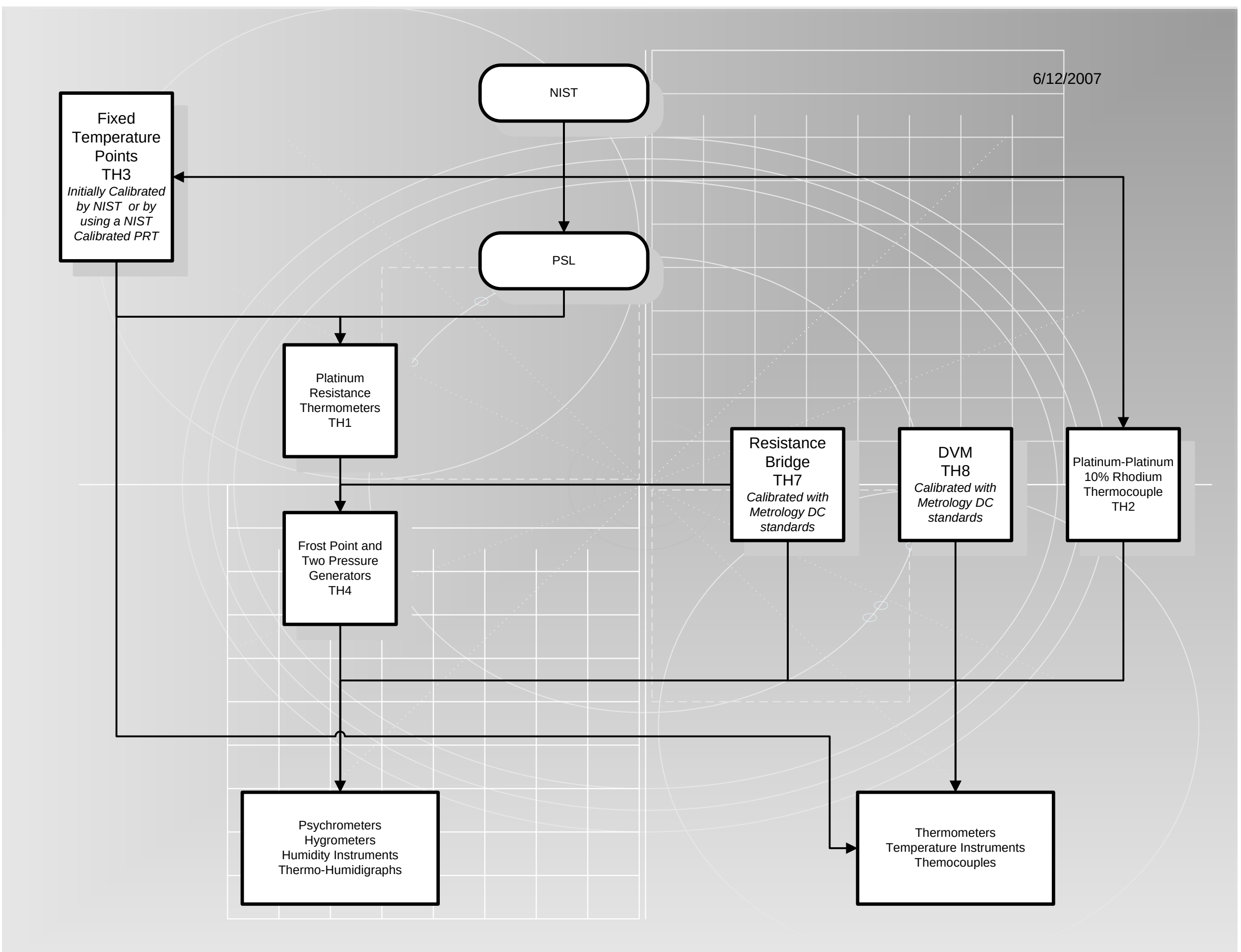
The dew/frost point temperature and the ambient air temperature of the moist air are measured to determine absolute and relative humidity. Air flow through the test chamber can be varied from 0 to 140 SLPM.

Humidity Calibration Using the Two-Pressure Method

Temperature, Humidity Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Temperature	-183°C to +660°C	0.006°C to 0.02°C
	420°C to 1100°C	0.2% of reading
Fixed Point	-38.8344°C	0.001°C
	0.01°C	0.0005°C
	29.7646°C	0.0005°C

	156.5985°C	0.002°C
	231.928°C	0.002°C
	419.527°C	0.002°C
	660.3233°C	0.005°C
Humidity	-75°C to 10.0°C	0.5°C Frost/Dew Point
	5% RH to 95% RH	0.5% RH



Temperature, Humidity Calibration Traceability

Temperature, Humidity Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
TH1	Standard Platinum Resistance Thermometer	Leeds & Northrup	-186 to 0°C -40 to 420°C	0.02°C 0.006°C
TH2	Platinum - Platinum 10% Rhodium Thermocouple	Leeds & Northrup	0 to 1100°C	0.3°C increasing linearly to 1.6°C at 1450°C
TH3	Fixed Temperature Points			
	Mercury	Isotech	-38.8344°C	0.001°C
	TP Water	Jarrett	0.01°C	0.0005°C
	Gallium	Isotech	29.7646°C	0.0005°C
	Indium	Hart Scientific	156.5985°C	0.002°C
	Tin	Isotech	231.928°C	0.002°C
	Zinc	Hart Scientific	419.527°C	0.002°
TH4	Frost Point Generator	Thunder Scientific	-70 to 10°C	0.5°C Frost/Dew Point
	Two-Pressure Generator	Thunder Scientific	5 to 95% RH	0.5% RH
TH7	Resistance Ratio Bridge	ASL	0 to 1.2	1 ppm
TH8	DVM	Keithley	0 to 1000 Vdc	0.015% of reading + 4 digits

GAS

<u>Pressure</u>

Pressure gages are calibrated using dead-weight piston gages. The effective area of the 0 to 500 psi reference is determined by NIST. The effective area of the 0 to 15,000 psi reference is determined by PSL. The effective area of the 0 to 100,000 psi reference is determined at FM&T with NIST traceable standards. True mass for each reference is determined using the NIST Mass MAP program.

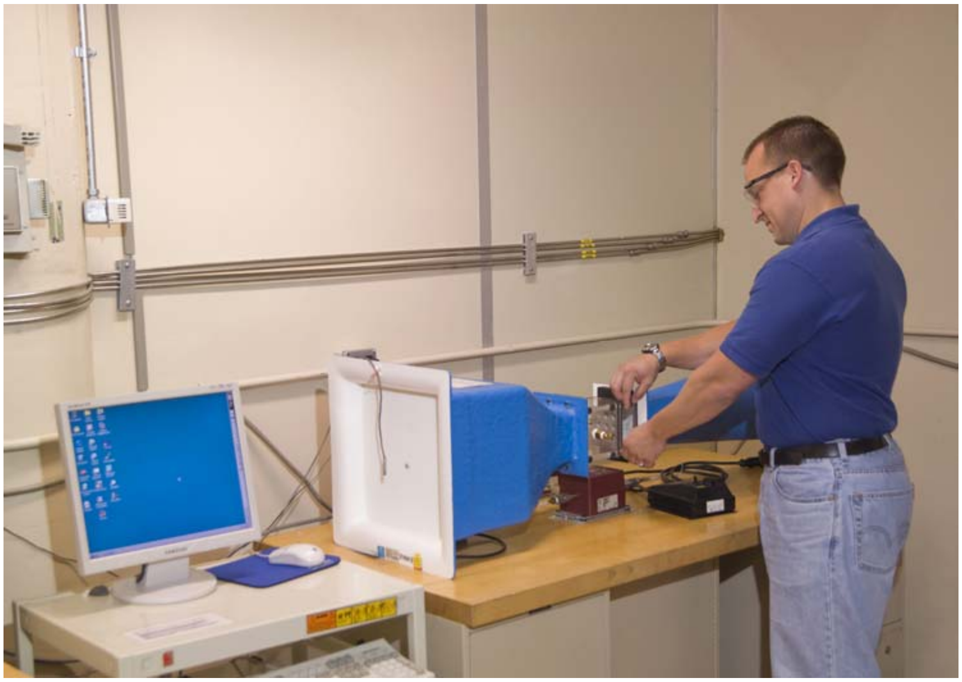
30,000 psig Gas Pressure Calibration

Gas Flow

Gas flow meters are calibrated by direct comparisons to PSL-certified flow meters or volumetric displacement devices. Volume, time, pressure, and temperature measurements are combined to obtain a value of flow. All measurement parameters are certified and NIST traceable.

Air Velocity

Air velocity meters are calibrated using a certified wind tunnel. The wind tunnel is calibrated using NIST-certified hot wire anemometer and pilot tube.



Air Velocity Calibration

Vacuum

Vacuum calibrations at or below 10^{-3} mmHg are performed using a molecular drag gage, sometimes called a spinning rotor gage (SRG). The SRG is calibrated by NIST.

Vacuum calibrations above 10^{-3} mmHg are performed using either a capacitance manometer or digital Quartz manometer, depending upon the range of the gage. The manometers are calibrated using a PSL-certified dead weight piston gage.

Vacuum Gage Calibration

<u>Gas Leaks</u>

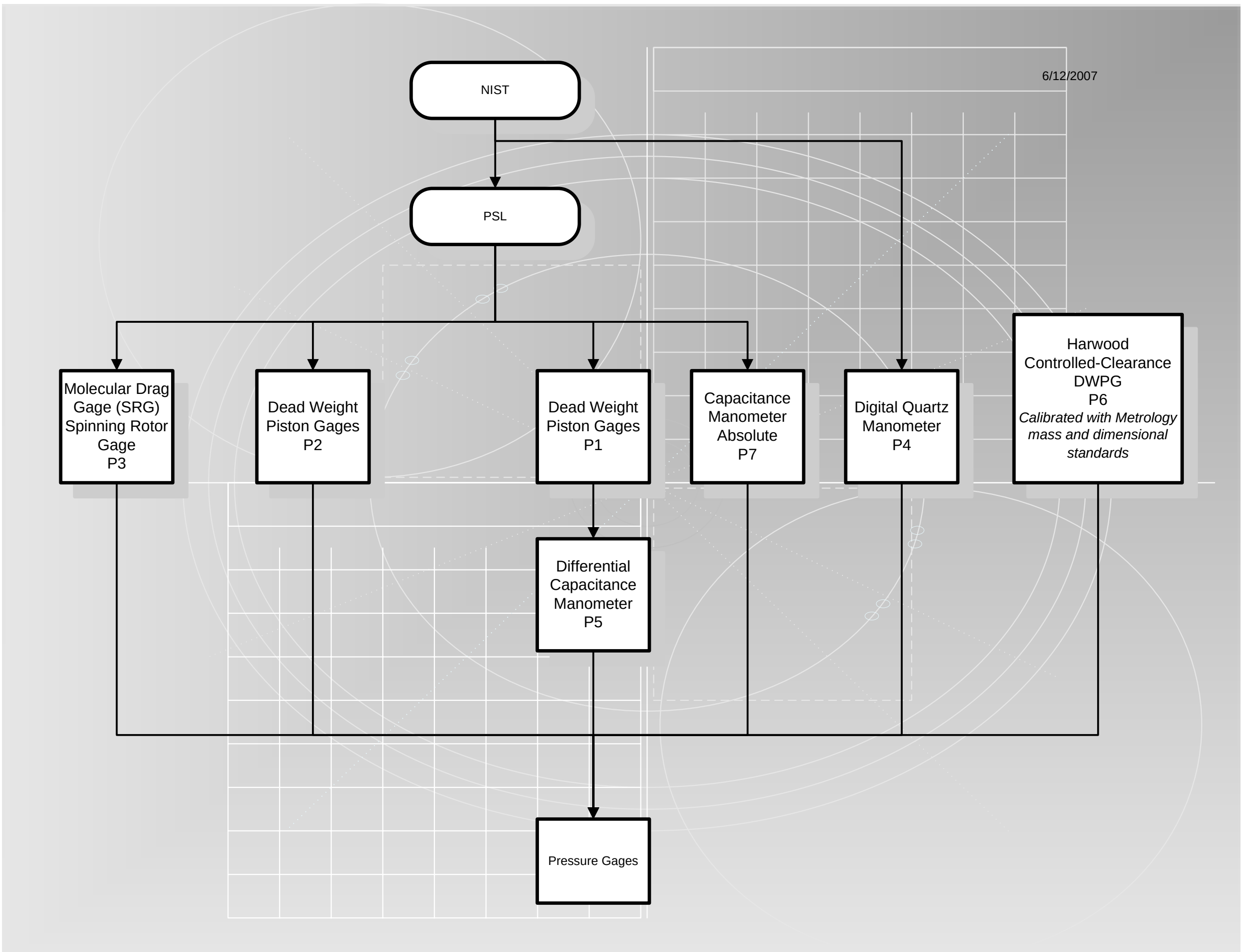
Gas leak devices are calibrated by making direct comparisons to PSL-certified leaks on a mass spectrometer or using the pressure, volume, temperature (PVT) technique. All measurement parameters of the PVT technique are certified and NIST traceable. A precision gas analyzer is used to evaluate the composition of the leak gas.

Standard Leak Calibration

Pressure Calibration Using Controlled Clearance Dead-Weight Piston Gage

Gas, Liquid Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Pressure	Absolute 10^{-8} to 10^{-4} torr 10^{-3} to 0.05 torr	 10% (0.0003 + 0.005 x reading) torr
	1 to 10 torr 10 to 1100 torr 0.1 to 500 psia	(0.0005 + 0.003 x reading) torr (0.03 + 0.0002 x reading) torr (0.01 + 0.0002 x reading) psi
	Gage 500 to 1800 psig 600 to 15,000 psig 15,000 to 100,000 psig	0.07% 0.06% 0.065%
Air Velocity	30 to 250 sfpm	4.5 sfpm + 1% of Reading
	251 to 1500 sfpm	6.0 + 1% of Reading
	1501 to 9500 sfpm	30 sfpm + 2% of Reading
Gas Flow	1 to 50,000 sccm 50 to 1800 slpm	1% 2%
Leak Rate	1 x 10^{-1} to 5 x 10^{-9} standard cm^3/s STP 10^{-10} standard cm^3/s STP	5 to 15% 25%



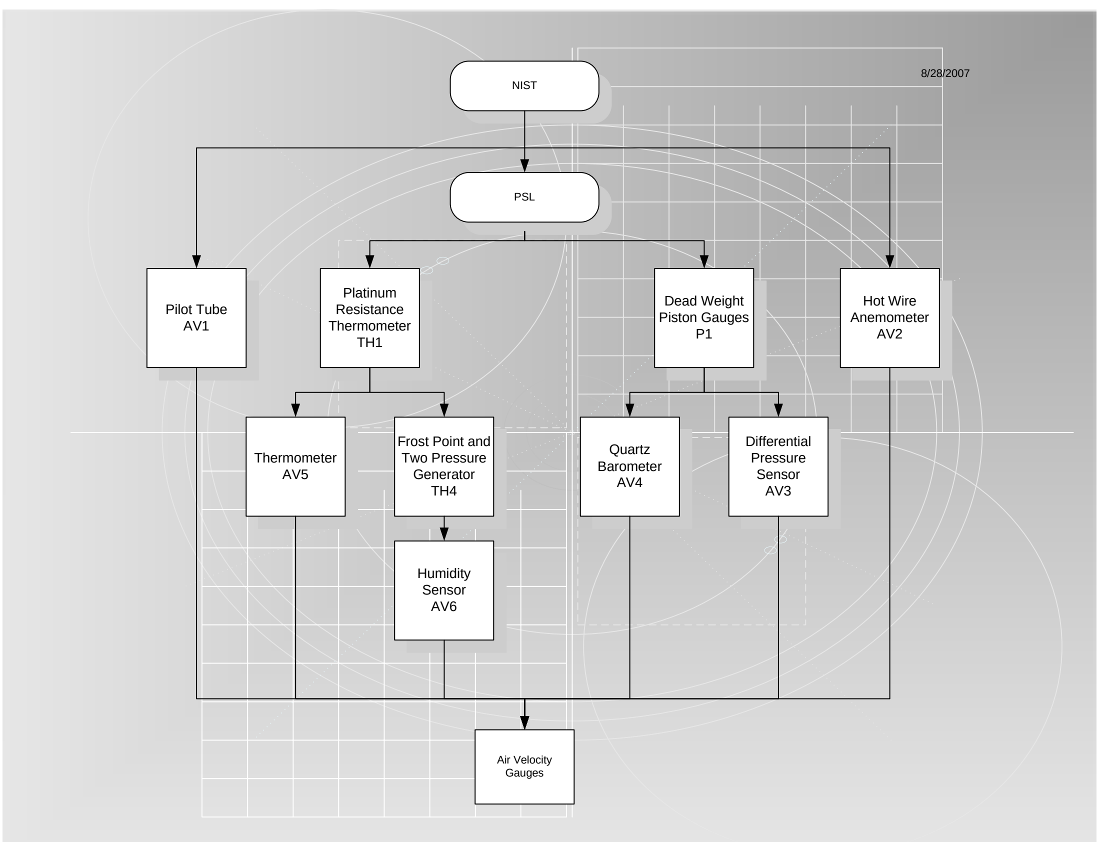
Pressure Calibration Traceability

Pressure Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
P1	Piston Gage	CEC	0.2 to 600 psi	0.015%
		DH Instruments	20 to 1800 psi	0.015%
P2	Piston Gages	Ruska	0.1 to 40,000 psig	0.02%
P3	Molecular Drag Gage	MKS	10^{-6} torr 10^{-5} torr 10^{-4} torr 10^{-3} torr 10^{-2} torr	8% 4% 3% 3% 3%

Pressure Standards

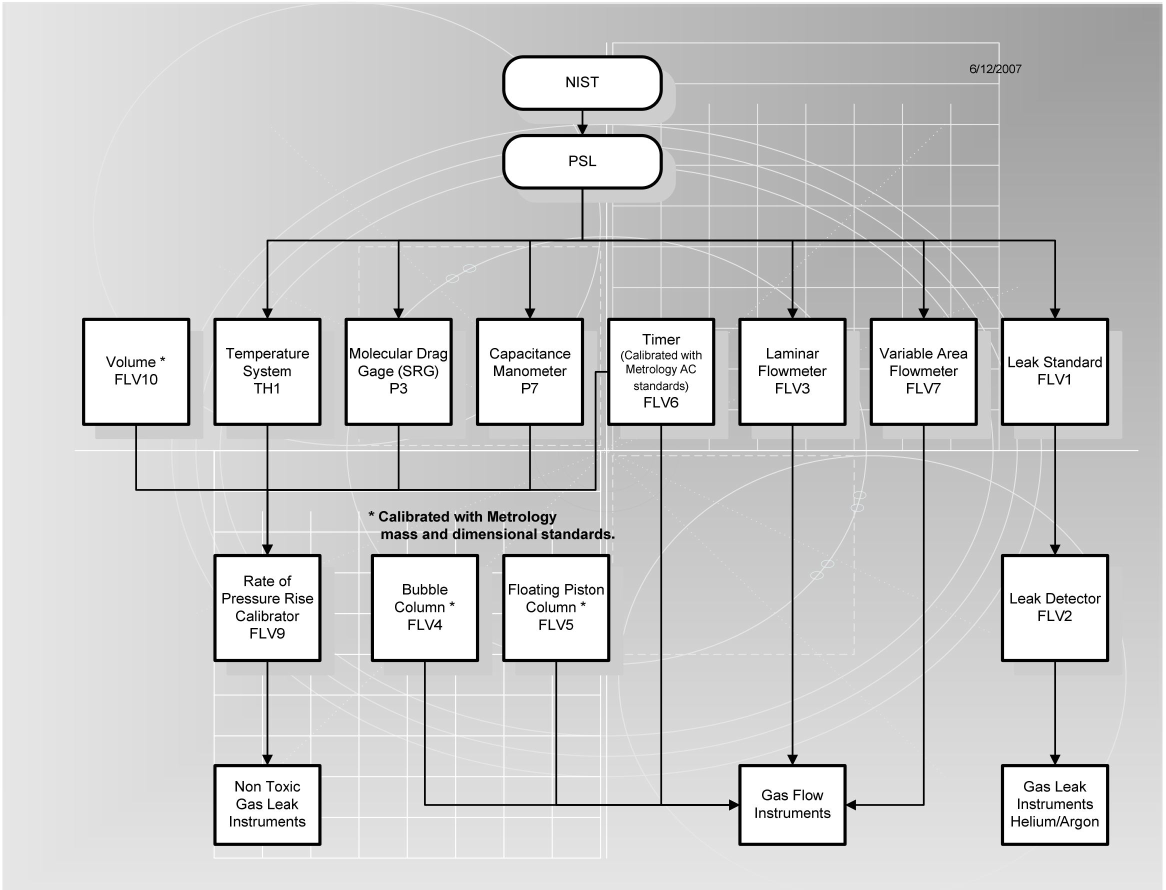
Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
P4	Digital Quartz Manometer (Differential) (remove)	Paroscientific	0.1 to 1100 torr -0 to 30 psia(remove)	(0.015 + 0.00005 x reading) torr (0.004 + 0.0001 x reading) psi(remove)
P5	Capacitance Manometer (Differential)	MKS	10^{-3} to 10 torr 10 to 100 torr	0.0005 + 0.00344* reading 0.0033 + 0.0026*reading
P6	Controlled-Clearance DWPG	Harwood	5000 to 100,000 psi	0.03% of reading
P7	Capacitance Manometer (Absolute)	MKS	10^{-3} to 0.1 torr 0.1 to 10 torr	0.00025+0.008*reading 0.0005+0.0055*reading



Air Velocity Calibration Traceability

Air Velocity Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
AV1	Pilot tube		1000 to 9500 sfpm	1.2 + 0.0007 Reading^0.5 + 647281/Reading^2 %
AV2	Hot Wire Anemometer	TSI	50 to 250 sfpm	2.05 + 1.35E-08 * Reading^3 + 1164.43 / Reading^2 sfpm
			25 to 1000 sfpm	5.44 + 0.00283 * Reading + 396.54 / Reading sfpm
AV3	Differential Pressure Sensor	MKS	0 to 10 Torr	0.004 * Reading
			10 to 100 Torr	0.32%
AV4	Barometer	Paroscientific		0.3 mmHg
AV5	Thermometer	Yellow Springs		0.1 °C
AV6	Humidity Sensor	FM&T		5%



Gas Leak, Flow Rate Calibration Traceability

Gas Leak, Flow Rate Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
FLV1	Leak Standard	Veeco/VIC/VTI	1×10^{-7} to 1×10^{-6} cm^3/s STP 1×10^{-9} to 9.9×10^{-8} cm^3/s STP 2×10^{-10} to 9.9×10^{-10} cm^3/s STP	4 to 8% 5 to 10% 9 to 15%
FLV2	Leak Detector	Vacuum Technology, Inc.	1×10^{-6} to 1×10^{-9} cm^3/s STP 1×10^{-9} to 2×10^{-10} cm^3/s STP	3% 3.5%
FLV3	Laminar Flow meter	National Instrument Laboratories	1 to 500 SLPM	1 to 2%
		CME	180 to 1800 SLPM	18 SCFM
FLV4	Bubble Column	Matheson Scientific	Volume 50 cm^3	0.05 cm^3
FLV5	Floating Piston Column	MKS	1 to 50,000 SCCM	0.25%
FLV6	Timer	Standard Electric	0 to 999 seconds	(0.1% + 1 count)
FLV7	Variable Area Flow meter	Fisher & Porter	8 to 23 SCFM	0.3 SCFM
FLV8	Standard Viscosity Oils	Cannon Instrument	0.3 to 5,300,000 mPa•s	0.58 to 0.83%
FLV9	Leak Calibrator (Rate of pressure rise)	VTI	1×10^{-3} to 1×10^{-7} cm^3/s STP	3 to 5%
FLV10	Volume	Whitey	25 to 1100 cm^3	0.1%

Electrical

DC Electrical Measurement

<u>DC Voltage</u>

The basic reference for DC voltage measurements consists of two groups of zener voltage references. Both groups are re-certified by intercomparison tests with a Josephson array voltage standard from the PSL. A precision potentiometer is used for voltage measurements to 10 volts. The potentiometer and a precision divider are used for measurements up to 1500 volts. High voltage dividers calibrated by the PSL or by NIST are used for measurements up to 150 kilovolts.

DC Voltage Inter-comparison

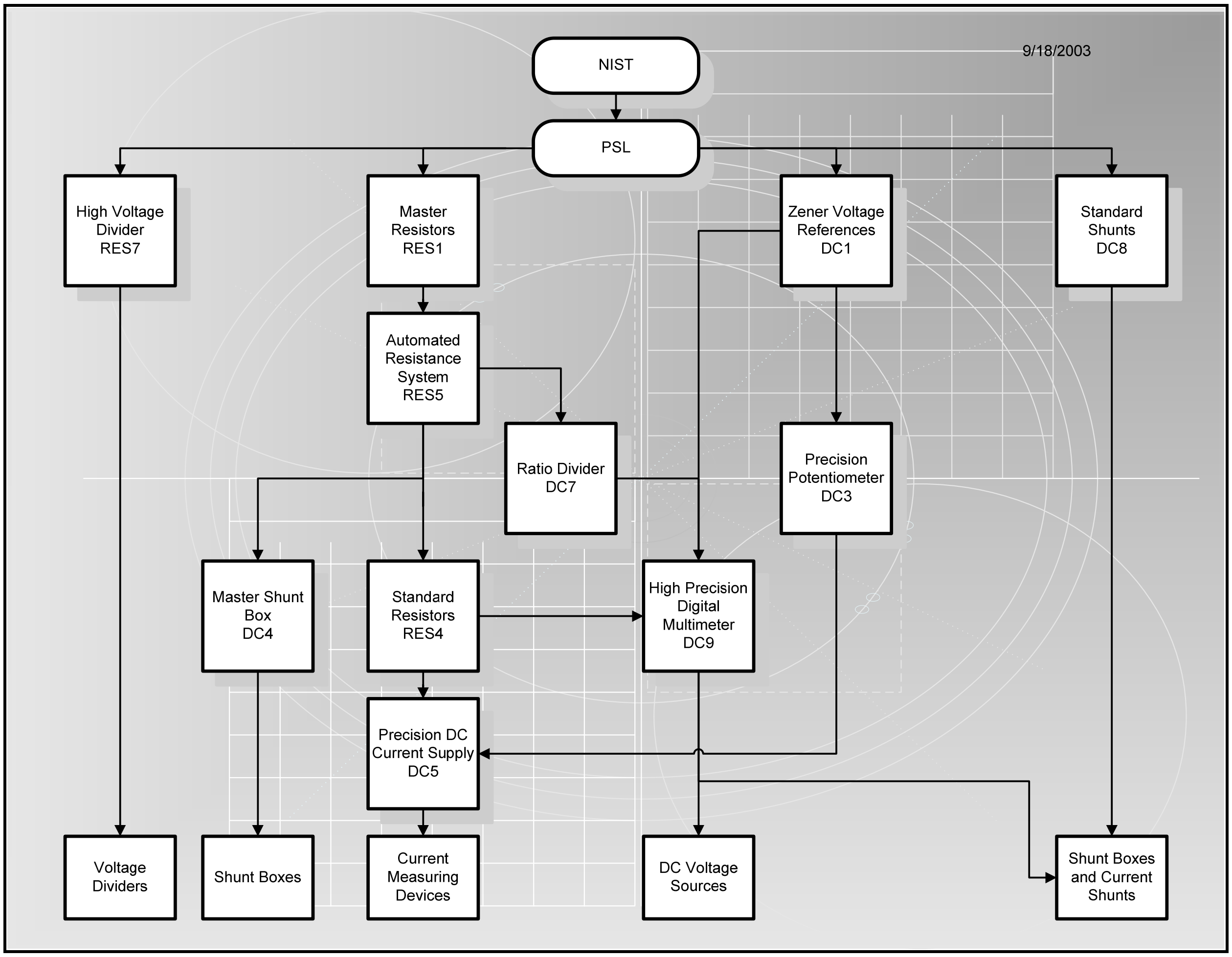
<u>DC Current</u>

Measurements of current up to 2 amperes are made using resistance and voltage standards. Shunts calibrated by the PSL are used for current measurements from 2 amperes to 300 amperes.

Automated Digital Multimeter Calibration

Electrical DC Measurement Capability

Type	*Range*	*Measuring Uncertainty (±) (k=2)*
DC Voltage	1.018 V 1 V 1 V to 1000 V 10 kV 100 kV 1.50 kV	0.41 ppm 0.45 ppm 3.1 ppm 137 ppm 150 ppm 260 ppm
DC Current	10^{-10} A 10^{-9} A 10^{-8} A 10^{-7} to 10^{-6} A 10^{-5} to 0.3 A >0.3 to 15 A >15 to 100 A >100 to 500 A	0.1% 0.1% 0.04% 0.04% 0.004% 0.005% 0.007% 0.008%
DC Resistance	10^{-4} to 10^{-1} Ω 10^{0} Ω 1 kΩ 1 to 100 Ω 100 to 1 MΩ 10^{7} Ω 10^{8} Ω	3.6 ppm 0.5 ppm 1.9 ppm 3.6 ppm 3.6 ppm 13.4 ppm 16.7 ppm
DC Magnetic Flux Density	Transverse Probe: 20 to 10,000 Gauss Axial Probe: 50 to 2000 Gauss	 2% to 4% 2% to 4%



DC Current, Voltage, and Ratio Traceability

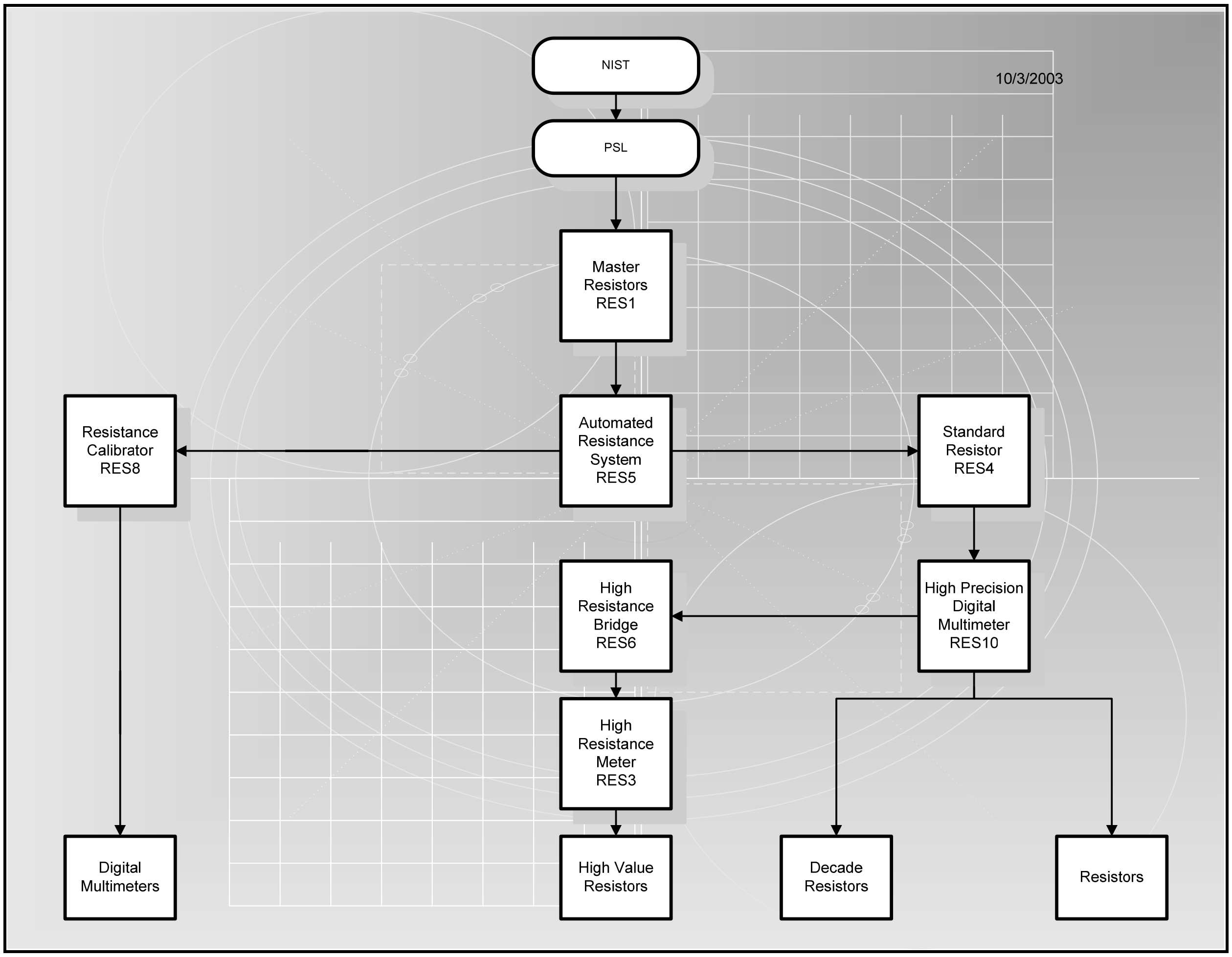
DC Current and Voltage Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
DC1	Zener Voltage References	Fluke	1.018 V and 10 V nominal	0.33 ppm
DC2	Voltage Dividers	Sensitive Research	10 to 100 kV	0.008% (Calibrated by NIST)
		Spellman	60 to 150 kV	0.02% (Calibrated by PSL)
		Fluke	1 to 10 kV	0.033% (Calibrated by Metrology)
DC3	Precision Potentiometer	Measurements International	0 to 10 V	(0.25 ppm + 0.0375 μV)
DC4	Master Shunt Boxes	Leeds & Northrup	0.015 to 15 A	33 ppm
DC5	Precision DC Current Supply	FM&T Metrology	1.5 μA to 15 A (7 ranges)	(0.02% or 1 nA), whichever is greater
DC6	Calibrated DC Voltage Source	Fluke	0 to 220 mV	8 ppm + 3 ppm of range
			>0.22 to 220 V	8 ppm + 0.5 ppm of range
			>220 to 1100 V	9 ppm + 0.5 ppm of range
DC7	Ratio Divider	Guildline	1:1 to 10,000:1	2 ppm
DC8	Shunt Standards	Leeds & Northrup Guildline	0 to 15 A 0 to 100 A 0 to 300 A 0 to 500 A	0.0033% 0.0066% 0.0066% 0.0066%
DC9	High Precision DMM	Hewlett-Packard	0.1 to 100 V 0.1 to 1000 V	25 ppm (Ratio) 11 ppm to 25 ppm (DC Voltage)

DC Resistance

The reference for resistance measurements is a Thomas 1 ohm and a 10 kohm standard resistor that are certified by the Sandia PSL. These resistors in conjunction with an automated resistance system are used to measure resistance from 0.001 ohm to 100 megaohm. From 100 megaohm to 10 teraohm, resistance measurements are accomplished using a high resistance meter.

Automated Resistance Measuring System



DC Resistance Traceability

DC Resistance and Ratio Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
RES1	Master Resistors	Leeds & Northrup ESI	1 Ω 10 kΩ	0.333 ppm 0.6 ppm
RES3	High Resistance Meter	Guildline	10^5 to 10^{12} Ω	150 ppm to 5000 ppm
RES4	Standard Resistors	Leeds & Northrup, Julie, Guildline	0.001 Ω to 100 MΩ	5 ppm to 25 ppm
RES5	Automated Resistance System	Measurements International	0.0001 Ω to 100 MΩ	0.1 ppm to 60 ppm (Ratio)
RES6	High Resistance Measuring System	Mid-Eastern	10^3 to 10^{13} Ω	0.2%
RES7	High Voltage Resistance Standard	Spellman	2000 x 10^6 Ω	0.02%
RES8	Multifunction Calibrator	Fluke	1 Ω to 100 MΩ	15 ppm to 100 ppm
RES9	High Precision DMM	Hewlett-Packard	10 Ω to 100 MΩ	25 ppm to 500 ppm

AC Electrical Measurement

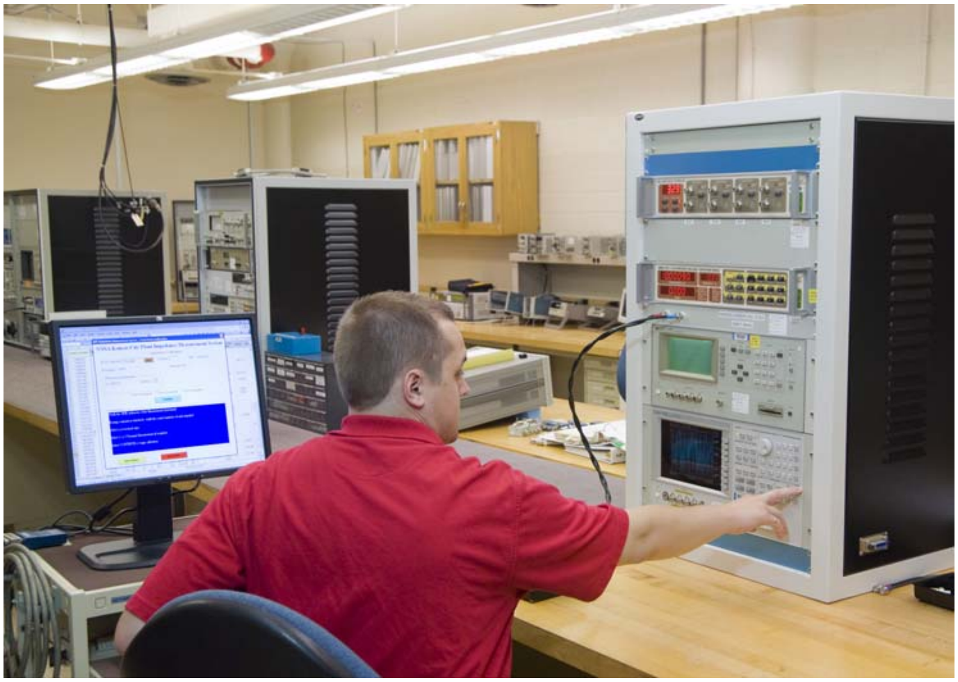
AC Voltage

AC voltage sources are calibrated using an alternating current measurement standard. The AC measurement standards are calibrated using a Fluke AC/DC Transfer Standards which is certified by the PSL.

Thermal voltage converter devices, including the AC/DC Transfer Standard, are certified for AC/DC difference by the PSL.

AC Current

AC current sources are calibrated using FM&T certified DC current sources and standard current shunts certified by the PSL. PSL certified AC resistors are used for currents less than or equal to 10 mA. The current through these resistors is established by measuring the voltage drop across the standard resistor using an AC voltmeter and calculating the current using a direct relationship.



Impedance Calibration

Capacitance and Inductance

Calibration of capacitors and inductors is made either through direct measurement or through a direct comparison with a certified standard of similar value. All comparison inductors and some of the comparison capacitors are certified by the PSL. The remaining capacitors are certified in-house using equipment identical to that used at the PSL.

Depending on the frequency and required uncertainty, capacitance measurements are completed on either the High-Precision Capacitance Meter, 1 kHz/MHz capacitance bridge or a Precision Impedance Analyzer. Inductance measurements are completed using the Precision Impedance Analyzer.

The measurement uncertainties for impedance vary with nominal value and frequency. Capacitance uncertainties may be as low as ±10 ppm and inductance uncertainties may reach ± 0.03%.

Frequency and Time

The frequency standard is established using one of two GPS receivers certified by the PSL. Each receiver is compared to the PSL primary frequency standard using the NIST Frequency and Analysis System. Frequency standards are used as references for standard counters and generators used for calibration. The comparator feature of the primary GPS receiver is used to certify rubidium frequency standards.

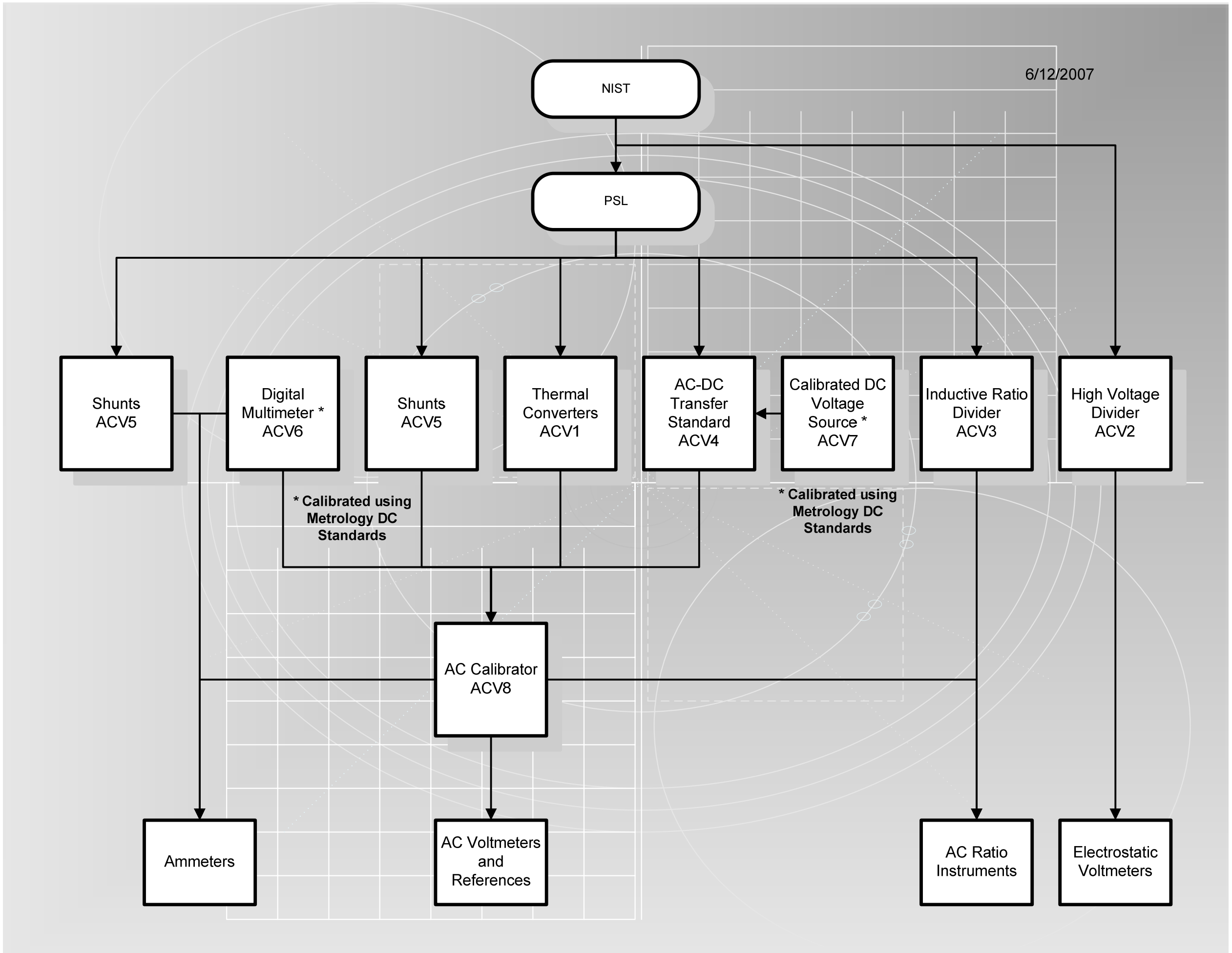
A digital clock is synchronized with the time information transmitted through GPS and is referenced to Universal Coordinated Time (UTC-NIST).

Computer-Controlled Counter Calibration

AC Measurement Capability

Type	***Range***	***Frequency***	***Measuring Uncertainty (±) (k=2)***
AC Voltage *	2.2 to 70 mV	10 Hz to 100 kHz	<0.12% + 2.5 V
	2.2 to 70 mV	100 kHz to 1 MHz	<0.35% + 8 V
	70 to 700 mV	10 Hz to 100 kHz	<0.03% + 2.5 V
	70 to 700 mV	100 kHz to 1 MHz	<0.11% + 8 V
	700 mV to 70 V	10 Hz to 300 kHz	<200 ppm
	700 mV to 70 V	300 kHz to 1 MHz	<1200 ppm
	70 V to 220 V	10 Hz to 500 kHz	<500 ppm
	220 V to 1000 V	10 Hz to 100 kHz	<800 ppm
	1 to 30 kV	60 Hz	0.066%
AC Current	10 mA to 20 A	10 Hz to 50 kHz	0.05 to 0.07%
Capacitance	0.001 pF to 1 μF	1 kHz	(0.01% + 0.00005 pF)
	1 to 10 μF	1 kHz	0.02%
	10 to 100 μF	1 kHz	0.5%
	1.0 to 1000 pF	1 MHz	0.1 to 0.2%
Inductance **	0.05 to 2 μH	10 kHz to 1 MHz	0.7% to 12%
	2 to 100 μH	10 kHz to MHz	0.7% to 3%
	100 μH to 10 H	1 kHz	0.04% to 0.4%
Frequency	1 Hz to 18 GHz		± 1.00 x 10^{-12}
Time of Day			0.5 ms

* Accuracy depending on range and frequency
** Accuracy depending on inductance and frequency



AC Current, Voltage, and Ratio Traceability

AC Current, Voltage, and Ratio Standards

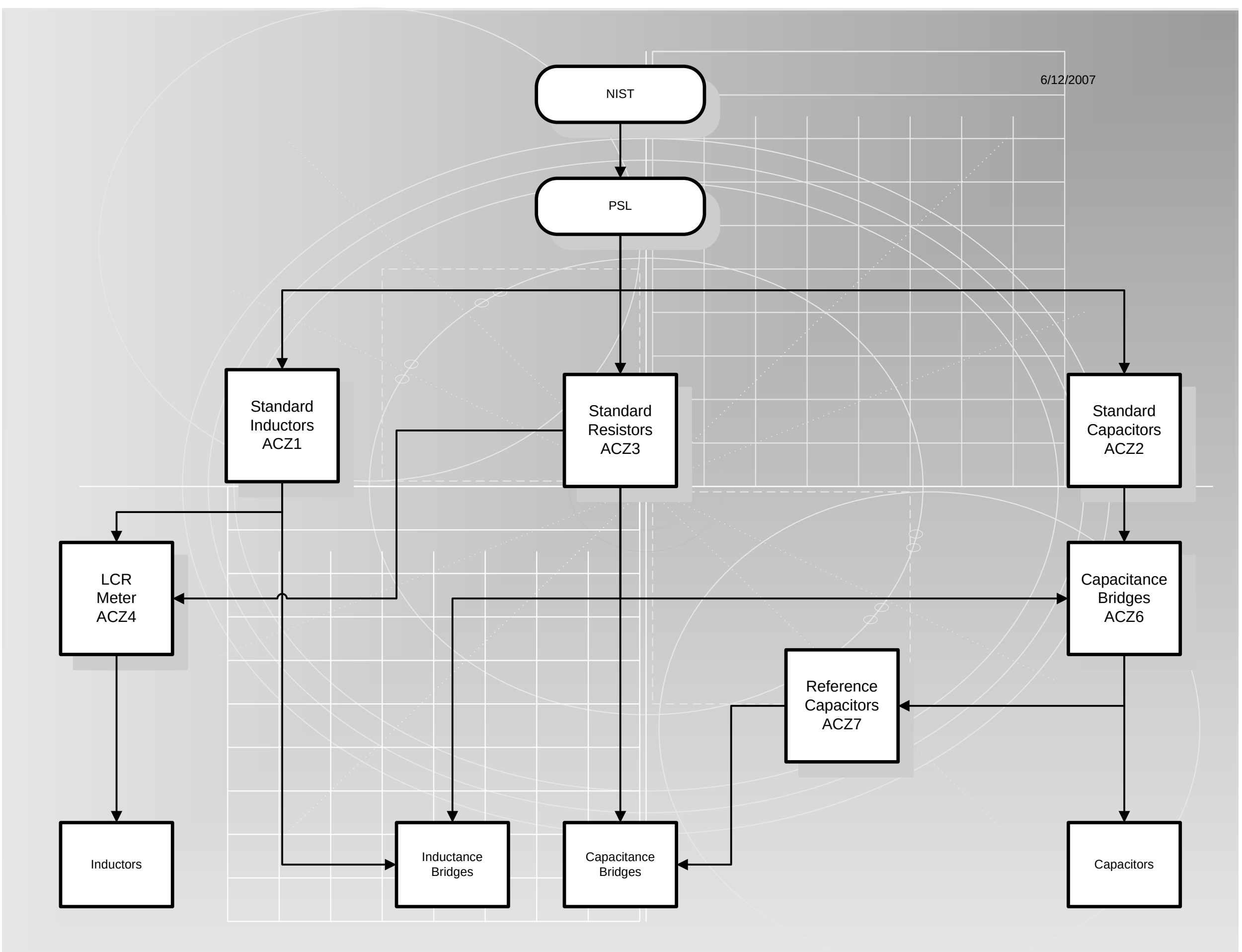
Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
ACV1	AC/DC Transfer Standard	Fluke	0.5 V to 1000 V (10 Hz to 1 MHz)	11 ppm to 153 ppm
	Thermal Voltage Converters	Ballantine	V (10 Hz to 100 MHz)	1 0.02 to 1.2%
ACV2	High Voltage Divider	Julie	20 to 100 kV	0.066%
ACV3	Inductive Ratio Divider	ESI	Ratio only, 0.1 ppm resolution (50 Hz to 10 kHz)	1 to 150 ppm

AC Current, Voltage, and Ratio Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
ACV4	AC Measurement Standard	Fluke 5790A	2.2 to 70 mV (10 Hz to 100 kHz)	<0.12% + 2.5 V
			2.2 to 70 mV (100 kHz to 1 MHz)	<0.35% + 8 V
			70 to 700 mV (10 Hz to 100 kHz)	<0.03% + 2.5 V
			70 to 700 mV (100 kHz to 1 MHz)	<0.11% + 8 V
			700 mV to 70 V (10 Hz to 300 kHz)	<200 ppm
			700 mV to 70 V (300 kHz to 1 MHz)	<1200 ppm
			70 V to 220 V (10 Hz to 500 kHz)	<500 ppm
			220 V to 1000 V (10 Hz to 100 kHz)	<800 ppm
			1 to 30 kV (60 Hz)	0.066%
ACV5	Shunts	Holt	10 mA to 20 A (10 Hz to 50 kHz)	0.05 to 0.07%
ACV6	Digital Multimeter	Hewlett Packard / Agilent	100 mV range	15 ppm + 10 ppm of range
			1 to 100 V ranges	10 ppm +1 ppm of range
			1000 V range	20 ppm +1 ppm of range
ACV7	Calibrated DC Voltage Source	Fluke	10 to 1000 V three ranges	<15 ppm
ACV8	AC Calibrator	Fluke	1 mV to 100 mV (10 Hz to 30 kHz)	0.02% of setting + 0.005% FS + 10 μV
			1 V to 100 V (10 Hz to 50 kHz)	0.02% of setting + 0.005% FS +10 μV
			1 mV to 100 mV (30 kHz to 100 kHz)	0.06% of setting + 0.006% FS +10 μV
			1 V to 10 V (50 kHz to 100 kHz)	0.06% of setting + 0.006% FS +10 μV
			1000 V range (50 Hz to 1 kHz)	0.06% of setting + 0.006% FS +10 μV

AC Current, Voltage, and Ratio Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
			1 mV to 100 mV (100 kHz to 1 MHz)	0.6% of setting + 0.1% FS
			1 V to 10 V (100 kHz to 1 MHz)	0.4% of setting + 0.1% FS
			100 V range (50 kHz to 100 kHz)	0.1% of setting
			Wideband output	
			10 to 30 Hz	0.3%
			>30 Hz to 1 MHz	0.25%
			>1 MHz to 20 MHz	0.75%
			>20 MHz to 30 MHz	1.0%
			to 2 A	0.07% of setting + 0.01% of range



Inductance and Capacitance Traceability

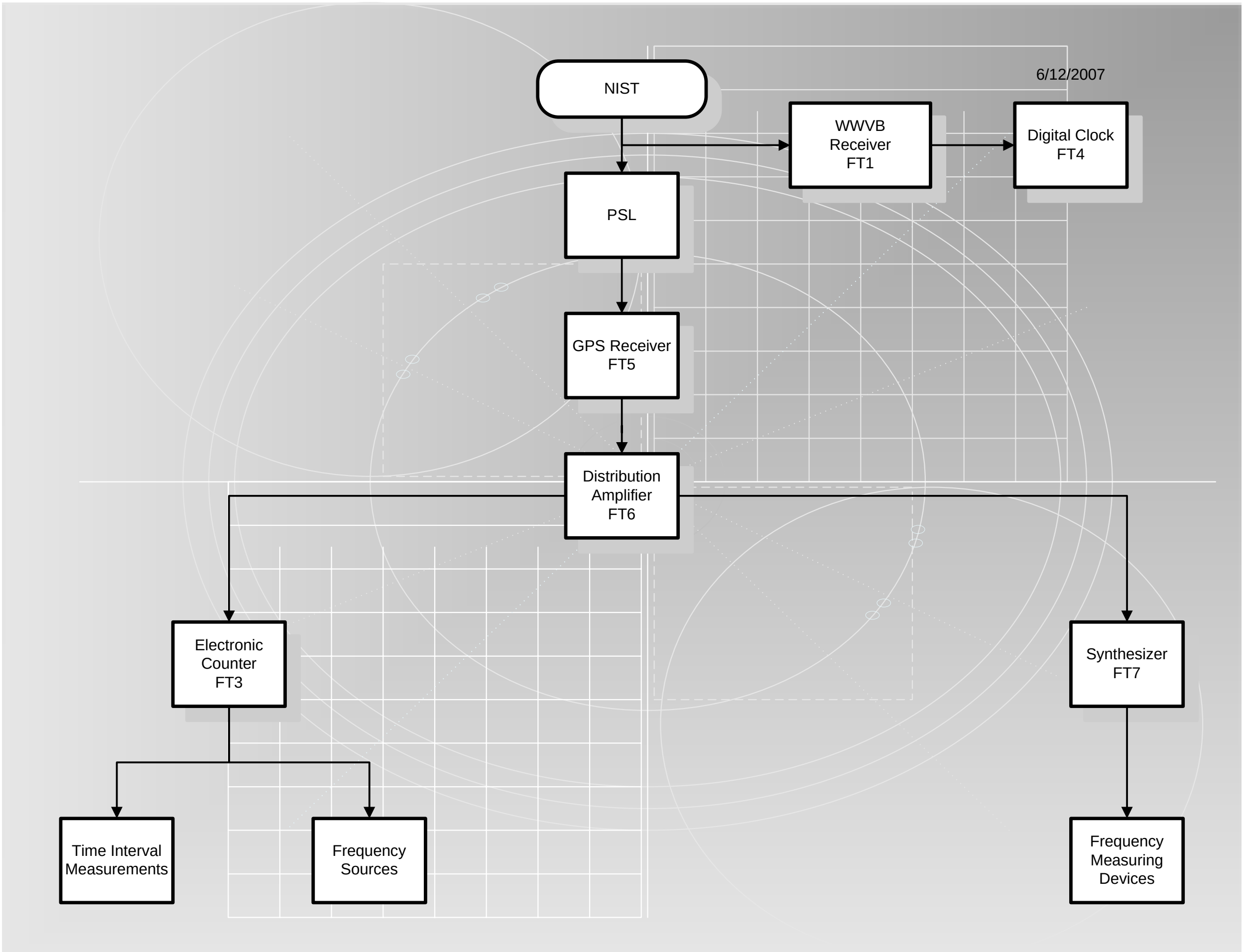
Inductance, Capacitance, and AC Resistance Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
ACZ1	Standard Inductors	General Radio, FM&T Metrology, Hewlett-Packard, Boonton	50 μH to 10 H 50 nH to 100 μH	0.03 to 0.3% * 0.3 to 10% *
ACZ2	Standard Capacitors	General Radio	1000 pF, fixed	0.003% at 1 kHz
		Andeen-Hagerling	10 pF, 20 pF, 40 pF, 50 pF	<± 9 ppm
ACZ3	Standard Resistors	Leeds & Northrup	1 to 20 kΩ	0.015%
		Hewlett-Packard	0.1 to 100 kΩ	0.5% ***
ACZ4	LCR Meter	Hewlett-Packard / Agilent	100 μH to 5H	0.10 to 0.3% (direct measurement)
			0.05 μH to 10 μH	0.1 to 10% (comparison to standard inductors)
ACZ6	Capacitance Bridge	Andeen-Hagerling	10 pF to 1 nF (160 Hz to 10 kHz) 10 pF to 1 nF (100 Hz to 10 kHz) 0.1 pF to 1 nF (1kHz)	± 10 ppm ± 10 ppm ± 10 ppm
		Hewlett-Packard	1 μF to 10 μF 0.1 to 1000 pF	0.1% at 1 kHz 0.2% at 1 MHz
ACZ7	Reference Capacitors	Boonton Electric General Radio FM&T Metrology	1 to 1000 pF 0.1 to 1000 pF 0.001 to 1 μF 1 to 10 μF in 1 μF increments	0.02% to 0.11% ** 0.1 to 0.15% ** 0.02% at 1 kHz 0.1% at 1 kHz
			10 to 100 μF in 10 μF increments	0.1% at 1 kHz

* Uncertainty depending on inductance value and frequency

** Uncertainty depending on capacitance value and frequency

*** Uncertainty depending on resistance value and frequency



Frequency and Time Traceability

Frequency and Time Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
FT3	Counter	Various	to 46 GHz	Used with GPS
FT4	Digital Clock	Symmetricom	24 hours	0.5 s
FT5	GPS Receiver	Hewlett Packard	10 MHz, 1 pps	5 parts in 10^{12}
FT8	GPS Receiver	Symmetricom	10 MHz, 1 pps	$\pm$ 1.00 x 10^{-12}

RF/Microwave Measurements

Air Lines

Air line impedance standards are calibrated using dimensional measurement techniques. The inner and outer conductors' diameters are measured using air gages, and the lengths are measured using a length measurement system by comparison to gage blocks of similar lengths. The dimensional measurements are used to calculate the impedance and electrical length.

Attenuators and Terminations

Standard attenuators and terminations are calibrated by NIST or the PSL and certified for calibrating Attenuation and Network Analyzer systems and to transfer their values by comparison to other attenuators and terminations.

Attenuator Calibration Using an Automatic Network Analyzer

Network Analyzers and Attenuation Systems

Network analyzers and attenuation systems are calibrated over their operating range by air lines and NIST-calibrated terminations and attenuators. They are used to calibrate single and multi-port devices for s-parameter measurements.

Noise Source

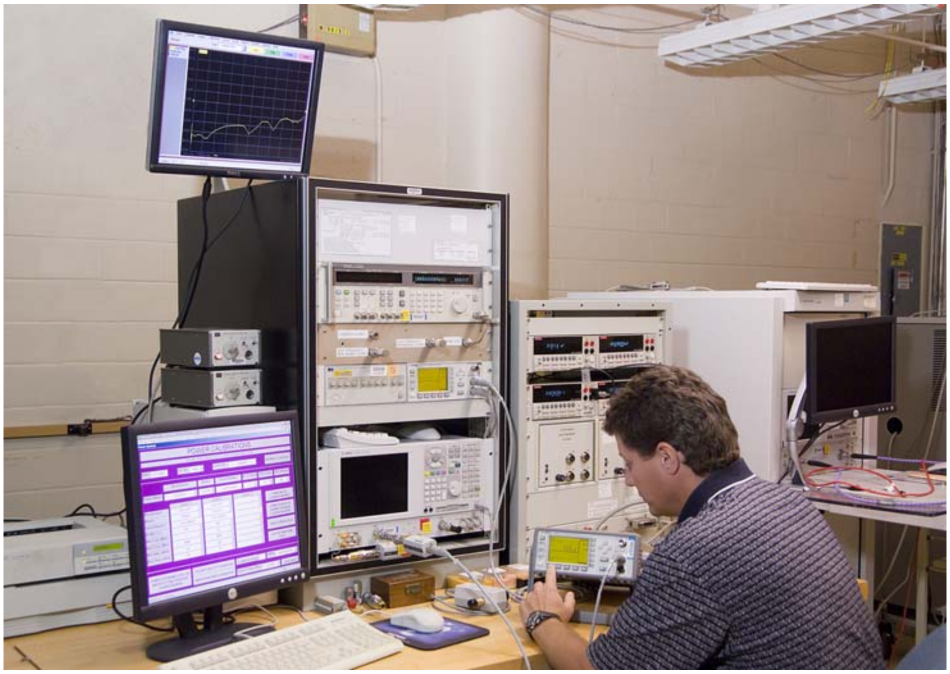
Standard noise sources are calibrated for excess noise ratio (ENR) across a frequency range at the PSL. They are used to transfer the ENR values by comparison to other noise sources.

Thermistor Mounts

Standard thermistor mounts are calibrated by PSL and certified for calibrating a Power Meter/Sensor Calibration system and transferring the calibration factor values by comparison to other thermistor mounts.

Power System

The power system is calibrated by transferring the calibration factors from PSL calibrated thermistor mounts to the systems reference sensor. The power system is used to calibrate power meters, sensors, and thermistor mounts.

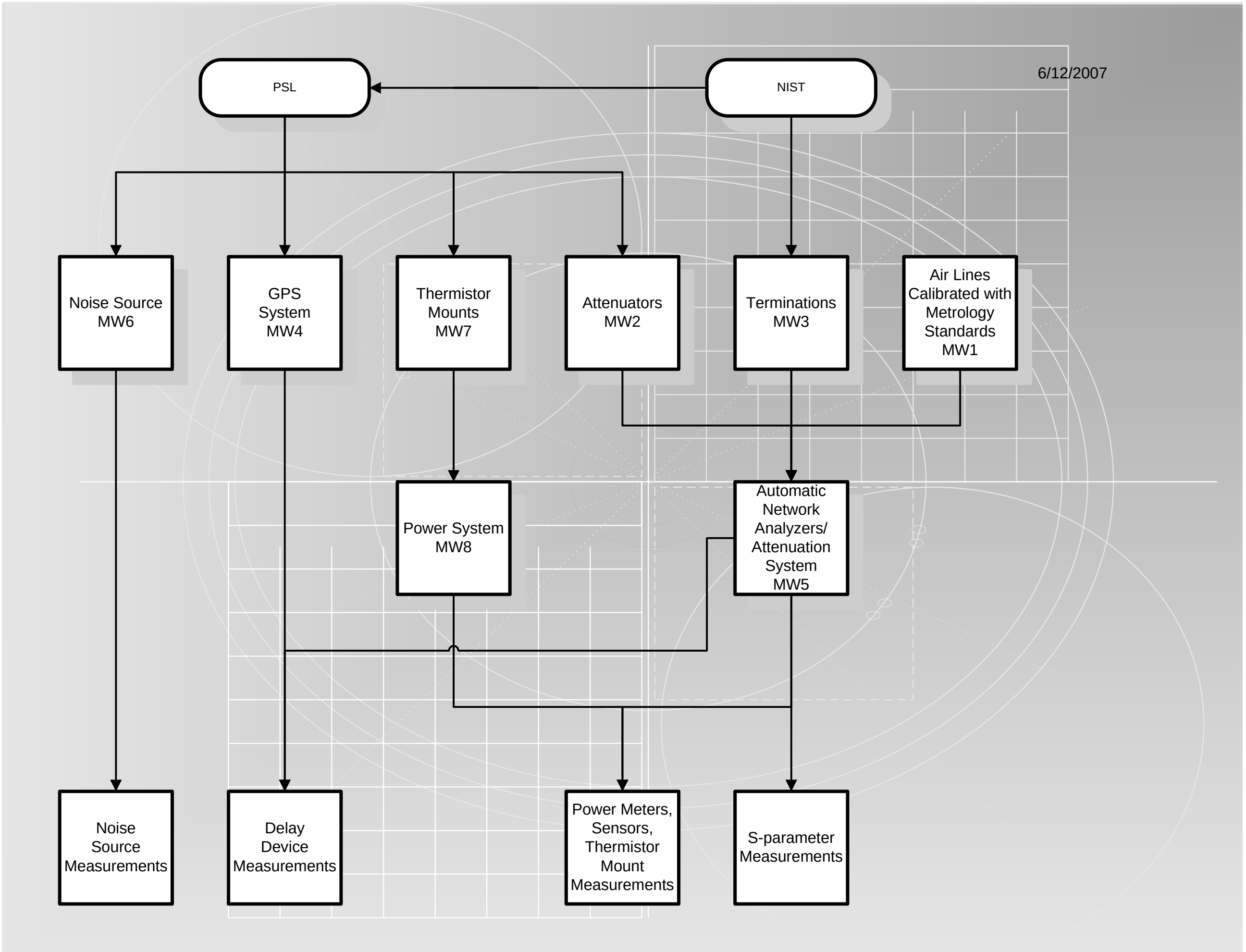


Power Meter Calibration

Electrical Radio Frequency/Microwave Measurement Capability

Type	***Range***	***Frequency***	***Measuring Uncertainty (±) (k=2)***
Air Lines (Air-Dielectric)	Impedance	50 MHz to 50 GHz	0.028 Ω to 0.22 Ω
	Electrical Length (3 to 30 cm)	50 MHz to 50 GHz	0.0017 cm to 0.042 cm
	Diameter (0.10 to 1.5) cm		(0.00013 to 0.00045) cm
	Physical Length (3 to 30) cm		(0.0010 to 0.0026) cm
Scattering Parameters[1]			
| |	$\|S_{ii}\|$, 0 to 1	300 kHz to 26.5 GHz	0.003 to 0.045
	$\|S_{ii}\|$, 0 to 1	> 26.5 GHz to 50 GHz	0.035 to 0.065
Phase	Arg(S_{ii}), -180° to 180°	300 kHz to 26.5 GHz	0.35° to 180°
	Arg(S_{ii}), -180° to 180°	> 26.5 GHz to 50 GHz	4.0° to 180°
Attenuation	$\|S_{ij}\|$, 0 dB to 110 dB	300 kHz to 18 GHz	0.01 dB to 1.5 dB
	$\|S_{ij}\|$, 0 dB to 80 dB	> 18 GHz to 26.5 GHz	0.07 dB to 1.5 dB
	$\|S_{ij}\|$, 0 dB to 70 dB	> 26.5 GHz to 50 GHz	Capability
Transmission Phase	Arg(S_{ij}), 0 dB to 70 dB	300 kHz to 50 GHz	Capability
Thermistor Mounts[1]	Calibration Factor (0.9 to 1.0)	1 MHz to 18 GHz	0.5% to 3%
CW Power Meter Systems[1]	1 nW to 100 mW	100 kHz to 18 GHz	2.4% to 5.7%
Peak Power Meter Systems[1]	10 µW to 100 mW	1 GHz to 2 GHz	7%
Group Delay[1]	1 ns to 1200 ns	50 MHz to 2.0 GHz	0.005 ns to 0.5 ns
Noise Sources[1]	ENR ~ 15 dB	60 MHz to 3.55 GHz	0.1 dB to 0.35

[1]Referenced to 50Ω + j0Ω.



Radio Frequency and Microwave Traceability

Radio Frequency and Microwave Standards

<table>
<tr><th>Code</th><th>Description</th><th>Manufacturer</th><th>Range</th><th>Uncertainty (k=2)</th></tr>
<tr><td>MW1</td><td>Air Lines</td><td>General Radio</td><td>3.5 mm, 7 mm, 14 mm, and</td><td>|Z| ± 0.028 to 0.22</td></tr>
<tr><td></td><td></td><td></td><td>Diameter (0.10 to 1.5) cm</td><td>± 0.00013 cm to 0.00045 cm</td></tr>
<tr><td></td><td></td><td></td><td>Physical length (3 to 30) cm</td><td>± 0.0010 cm to 0.0026 cm</td></tr>
<tr><td></td><td></td><td>Maury Microwave</td><td>50 MHz to 26.5 GHz</td><td>E.L. ± 0.0017 cm to 0.042 cm</td></tr>
<tr><td>MW2</td><td>Attenuators</td><td>Hewlett Packard</td><td>10 dB, 300 kHz to 26.5 GHz</td><td>± 0.008 dB to 0.042 dB</td></tr>
<tr><td>MW3</td><td>Terminations</td><td>General Radio
Wiltron</td><td>300 kHz to 100 MHz</td><td>| | ± 0.0008 to 0.003
± 0.2° to 180°</td></tr>
<tr><td>MW4</td><td>GPS Receiver</td><td>Hewlett Packard</td><td>10 MHz</td><td>± 0.000 005 ppm</td></tr>
<tr><td>MW5</td><td>Network Analyzers</td><td>Hewlett Packard</td><td>300 kHz to 50 GHz</td><td>| | ± 0.001 to 0.065</td></tr>
<tr><td></td><td></td><td></td><td>| |, 0 to 1;
, -180° to 180°</td><td>± 0.35° to 180°</td></tr>
<tr><td></td><td></td><td></td><td>Attenuation: 0 to 110 dB
300 kHz to 26.5 GHz</td><td>± 0.01 to 1.5 dB</td></tr>
<tr><td>MW6</td><td>Noise Source</td><td>Hewlett Packard</td><td>60 MHz to 3.55 GHz</td><td>± 0.1 to 0.35 dB</td></tr>
<tr><td>MW7</td><td>Thermistor Mounts</td><td>Hewlett Packard</td><td>1 MHz to 18 GHz</td><td>± 0.3% to 1.5%</td></tr>
<tr><td>MW8</td><td>Power System</td><td>FM&T Metrology</td><td>1 MHz to 18 GHz</td><td>± 1.0% to 2.5%</td></tr>
</table>

Optical and Radiation

Optical Radiometric Measurement

Radiometry is the measurement of radiation in the optical spectrum, which includes ultraviolet, visible, and infrared light. The main radiometric reference standards at FM&T are heat-flow calorimeters and wavelength standards, which include Helium-Neon (HeNe) lasers and Mercury spectral lamps. The PSL calibrates the heat flow calorimeters. The HeNe laser wavelength standard is calibrated by NIST because of its low uncertainty. The mercury spectral lamps do not require calibration because of their physical characteristics. Measurements performed include incoherent measurement in the ultraviolet and visible regions of the optical spectrum and coherent measurements, which consist of HeNe, Nd:YAG, and CO_2 lasers. Power levels of these measurements range from fractions of a microwatt to levels in excess of 1000 watts over wavelengths of 365 nm to 10.6 m. Most of the radiometric calibration activity at FM&T is calibrating Nd:YAG laser power sensors and meters in CW mode.

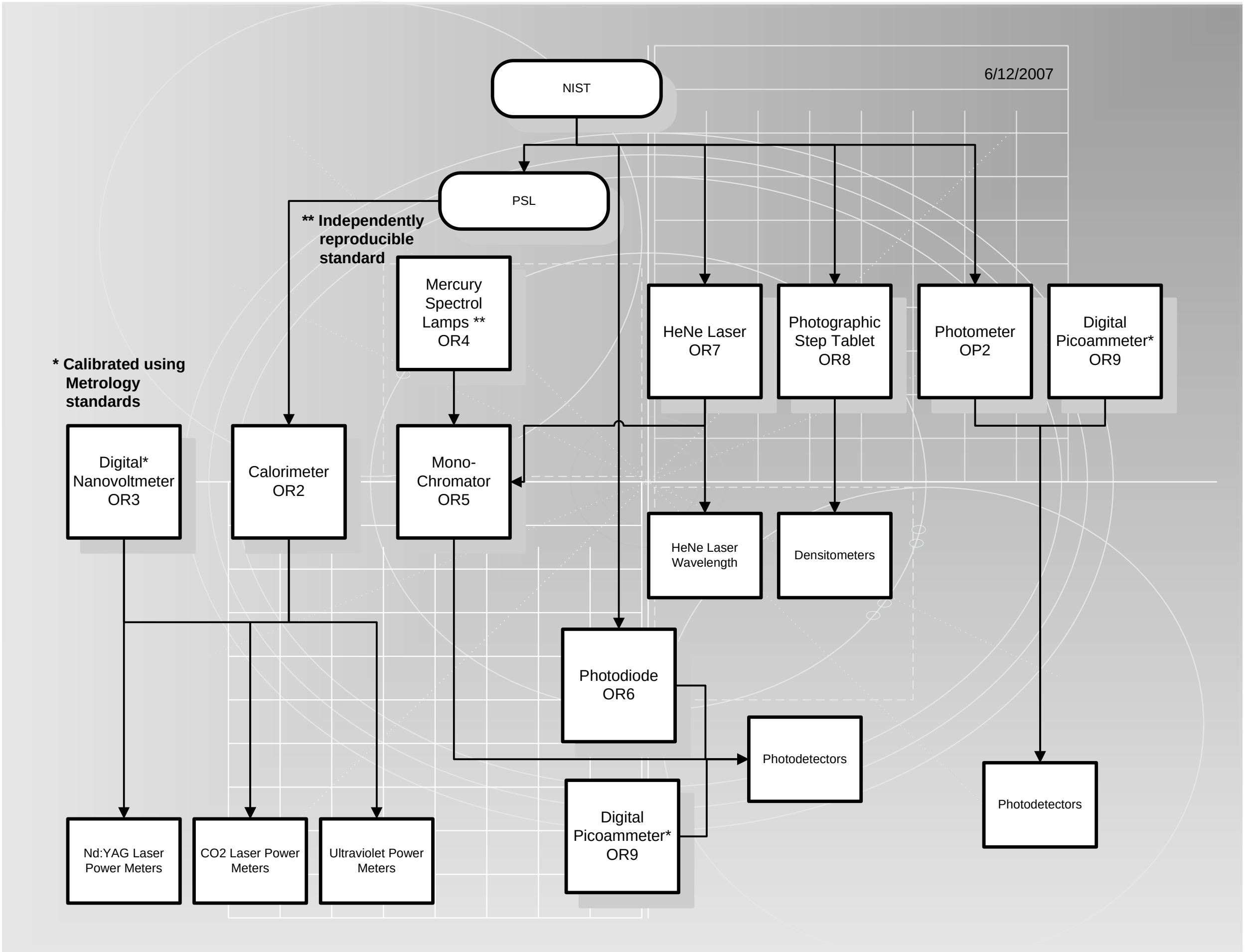
Laser Wavelength Calibration

Optical Photometric Measurement

Photometry is the measurement of visible light intensity and energy as it affects the human eye. The photometric reference standards at FM&T are standard photometers, calibrated by NIST. Standard photometers output current and are used with a digital picoammeter to measure illuminance in units of foot-candles or lux.

Optical Measurement Capability

Type	***Range***	***Measuring Uncertainty (±) (k=2)***
Laser Power	λ = 1064 nm, 0.2 to 10 W λ = 1064 nm, 1 to 25W	1.0% 3.0%
Laser Energy (Average)	λ = 1064 nm, 2 mJ to 20 J	1.0%
UV Irradiance UV Energy Density	λ = 365 nm, 0 to 2 mW/ cm^2 λ = 365 nm, 0 to 120 mJ/ cm^2	3.0% 3.0%
Photo detector Responsivity	λ = 570 to 910 nm	1.0%
Ultraviolet Irradiance	λ = 365 nm to 1100 nm 0.1 to 10 mW/cm^2	3.0%
Laser Measuring System	λ = 632.8 nm (HeNe)	(Distance) 1.8 ppm of displayed value + 1 count
X-Ray Film Density	0 to 4 Optical Density Units	(0.03 density units + 1% of reading)
HeNe Laser Wavelength	632.991 370 nm	0.027 ppm
Illuminance	1 to 800 foot-candles	2.3%



Optical Traceability (Radiometric)

Optical Radiometric Measurement Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
OR2	Calorimeter	Scientech	1 mW to 10 W 365 nm to 1100 nm 10.6 μm	 1.0% 2.7%
OR3	Digital Nanovoltmeter	Keithley	10mV to 10 V	(0.01% of reading + 4 ppm of range)
OR4	Mercury Spectral Lamp	Oriel	237.8 to 1092.2 nm	0.1 nm
OR5	Monochromator	Various	235 to 1092.2 nm	1.0 nm
OR6	Photodiode	Hamamatsu	400 to 910 nm	0.45% to 0.28%
OR7	HeNe Laser	Hewlett Packard	632.991 370 nm	11 ppb
OR8	Photographic Step Tablet	NIST	0 to 4 density units	0.0075 Optical density units
OR9	Digital Picoammeter	Keithley	200 nA to 20 mA	(0.2% of reading + 10 digits) to (0.1% of reading + 10 digits)
OP2	Standard Photometer	Graseby	1 to 800 foot-candles	1.7%

Nd:YAG Laser Power Meter Calibration